

Detectors for Future Missions: Increasing Scale, Extending Performance, and Integrating Functions

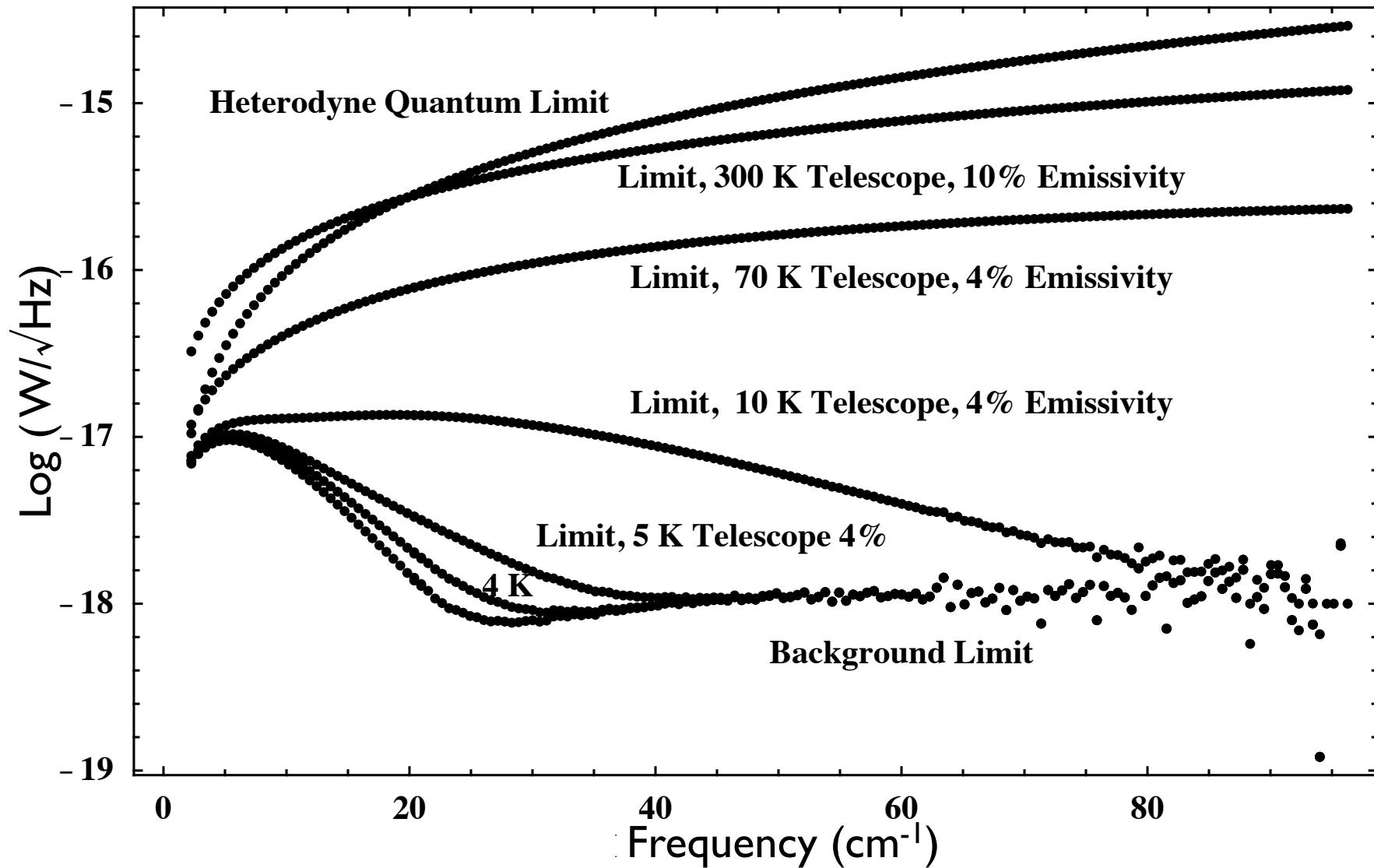
Harvey Moseley
With thanks to many contributors

Detectors For Space Applications

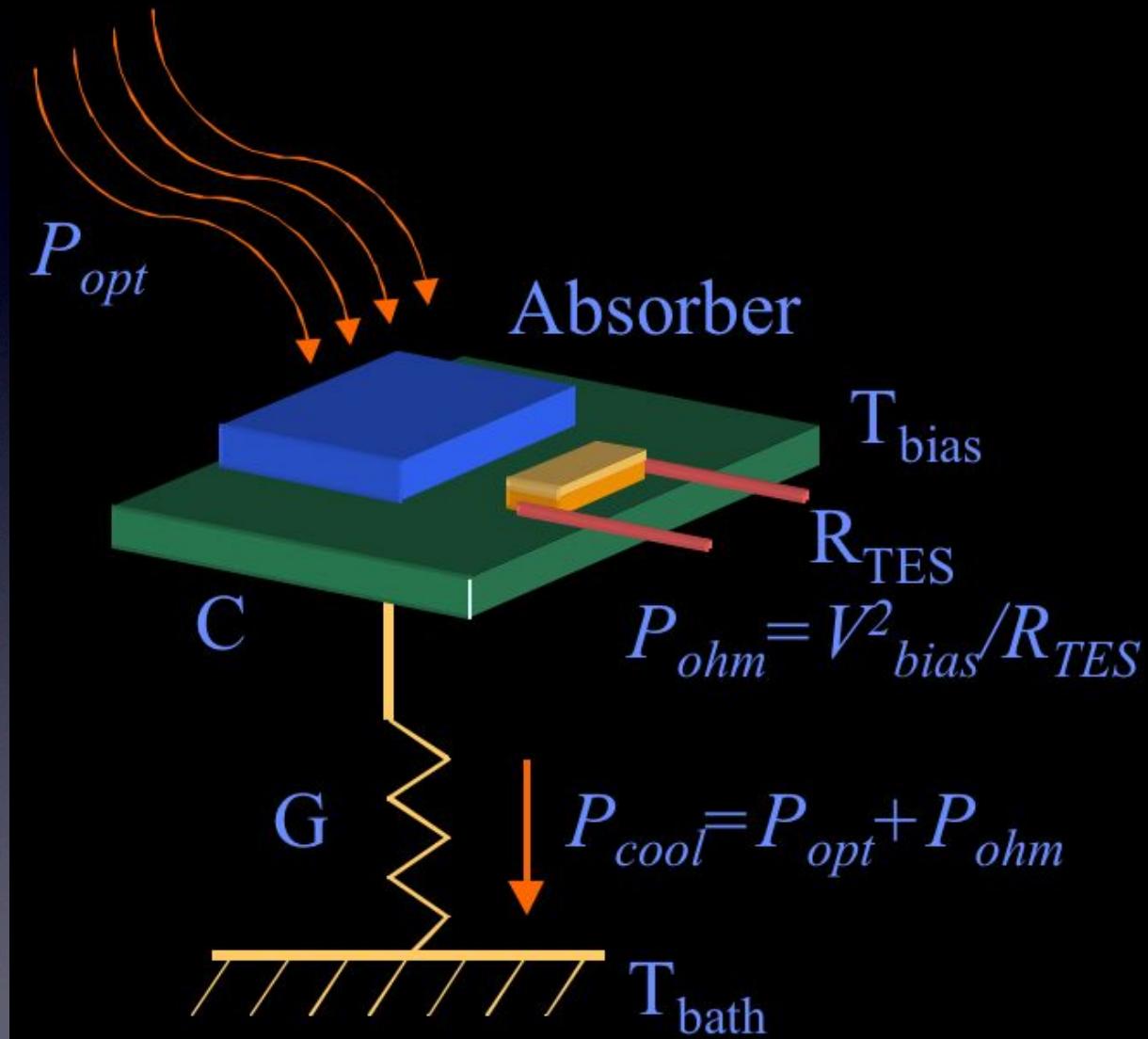
- The information content in an observation scales as the number of photons detected, which goes as $A\Omega$.
 - Maximize the number of beams on the sky
 - Limited by focal plane area, technical limitations, or budget
 - Spectroscopy brings in an additional dimension
 - Best sensitivity with a background-limited detector per spectral resolution element
 - FTS and Heterodyne provide spectroscopy with one detector per beam, but with cost in sensitivity.
 - Space applications impose additional requirements:
 - Performance in ionizing radiation environment
 - Overall power limitations
 - Data Rate?

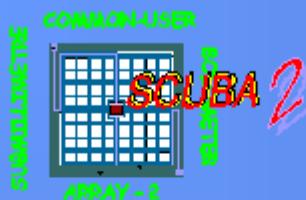
The Far IR Sky is Dark

NEP for Diffraction Limited Beam, 20% Bandwidth

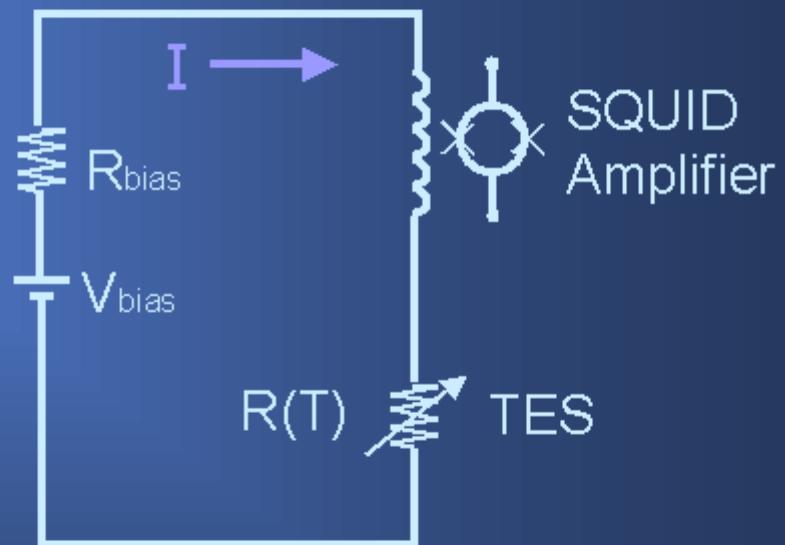
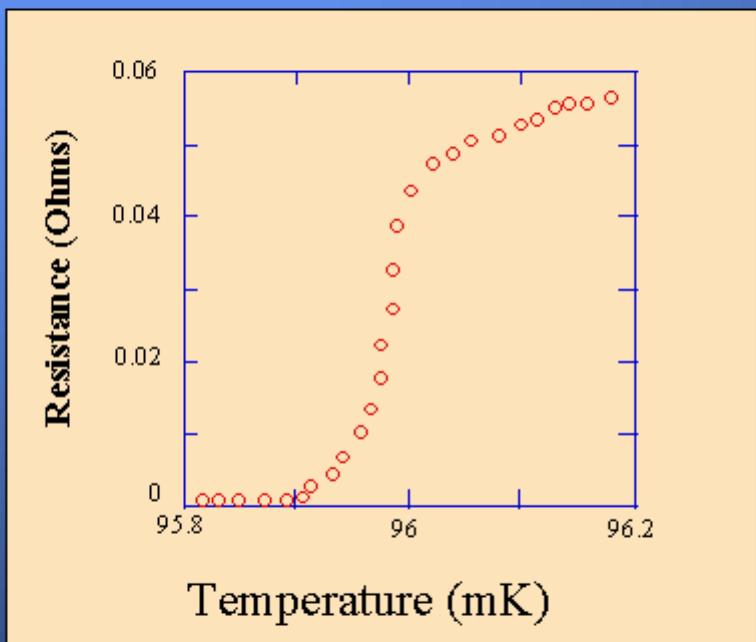


Bolometer Schematic



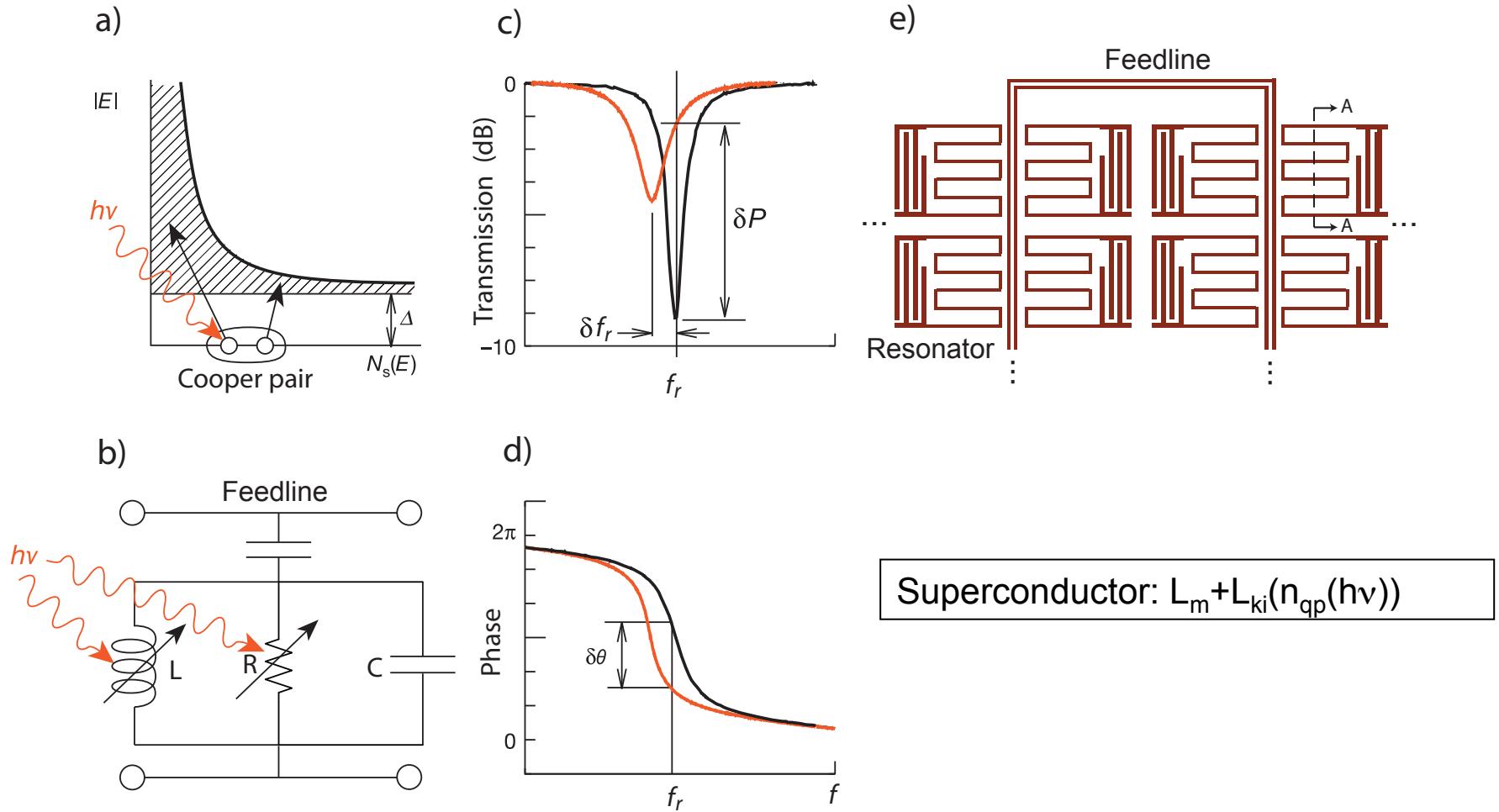


Voltage-Biased Superconducting Transition-Edge Sensors

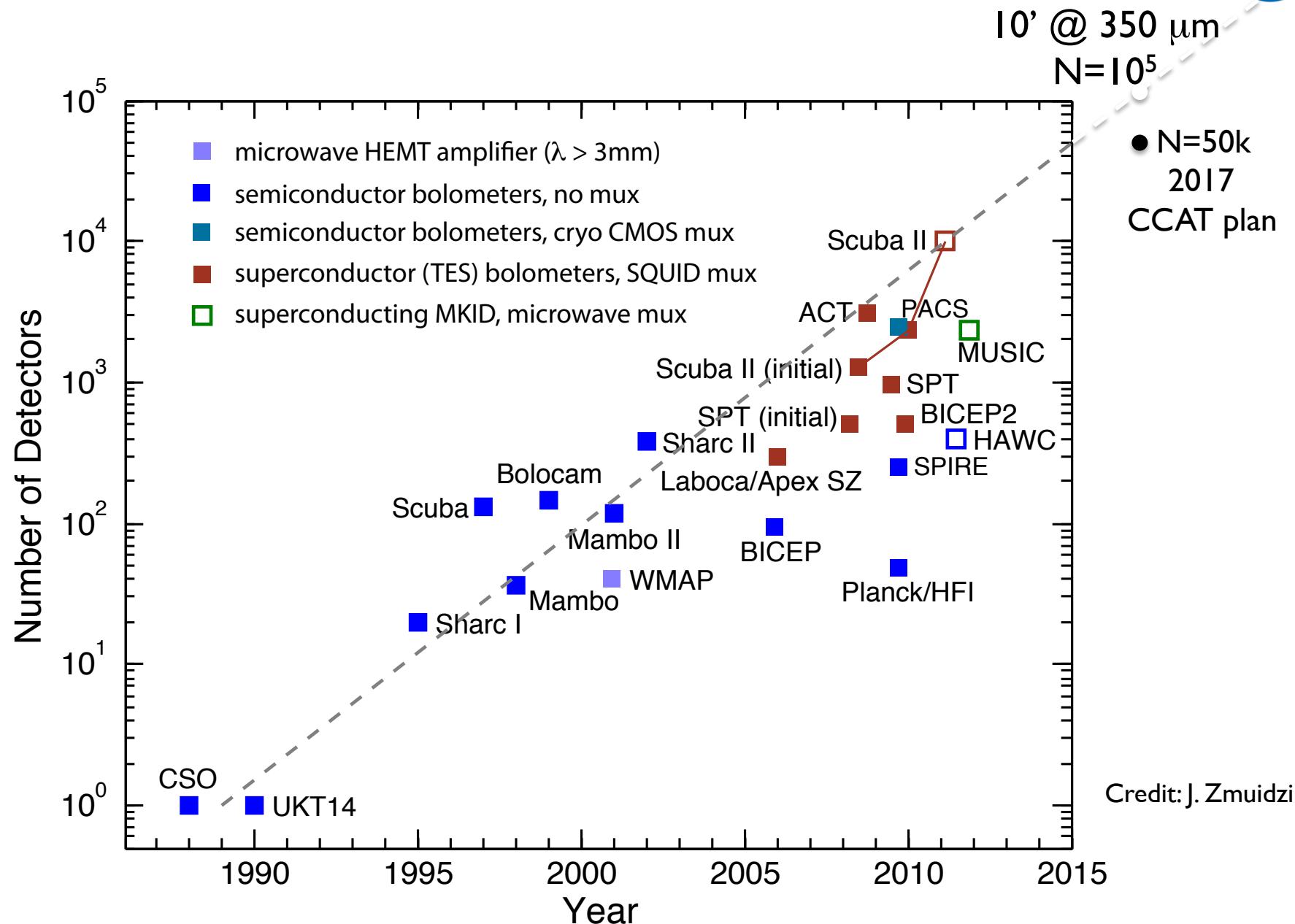


- Voltage-biased on normal - superconducting transition
- Resistance is a very steep dependence on temperature in transition region
- Film held at constant voltage bias - change in resistance results in a change in current through the film

Superconducting microwave resonators for photon detection *a.k.a Microwave Kinetic Inductance Detector (MKID)*



P. Day et al, *Nature* 425, 2003 (JPL, Caltech)



Parsing the Chart

- The first generation of instruments used an amplifier-per-detector approach with up to ~ 400 pixels.
 - Slope had been small – similar FIR imagers and spectrometers were operating on the KAO in the late 1980s with ~100 detectors
- Advent of SQUID multiplexers (1998) and microresonator readouts (2003) have put us on a different slope

Moving to Larger Arrays

Technical Implications

- Focal plane area – total number of modes
 - Parametric uniformity of detectors
 - Cryogenic optical input (gigantic windows are challenging, especially for ground based/suborbital)
 - Large scale cryo optics/AR coating
 - How to match to telescope
 - Large scale input filtering
 - Readout electronics

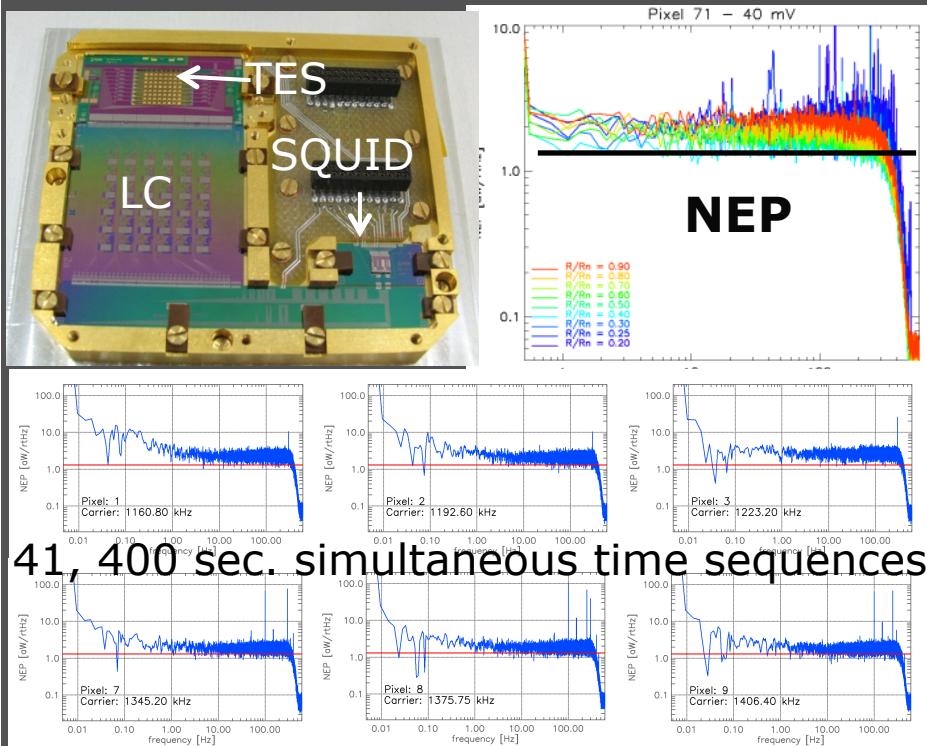
Sensitivity

- $\text{NEP}_d < \text{NEP}_p$
- Optical efficiency
- Beam coupling to optical system
 - Focal plane sampling vs beam coupling
 - Zmuidzinas, Appl. Opt. 2003 detailed analysis
 - *We know how to calculate performance: you just have to decide what you want*

Low NEP Developments

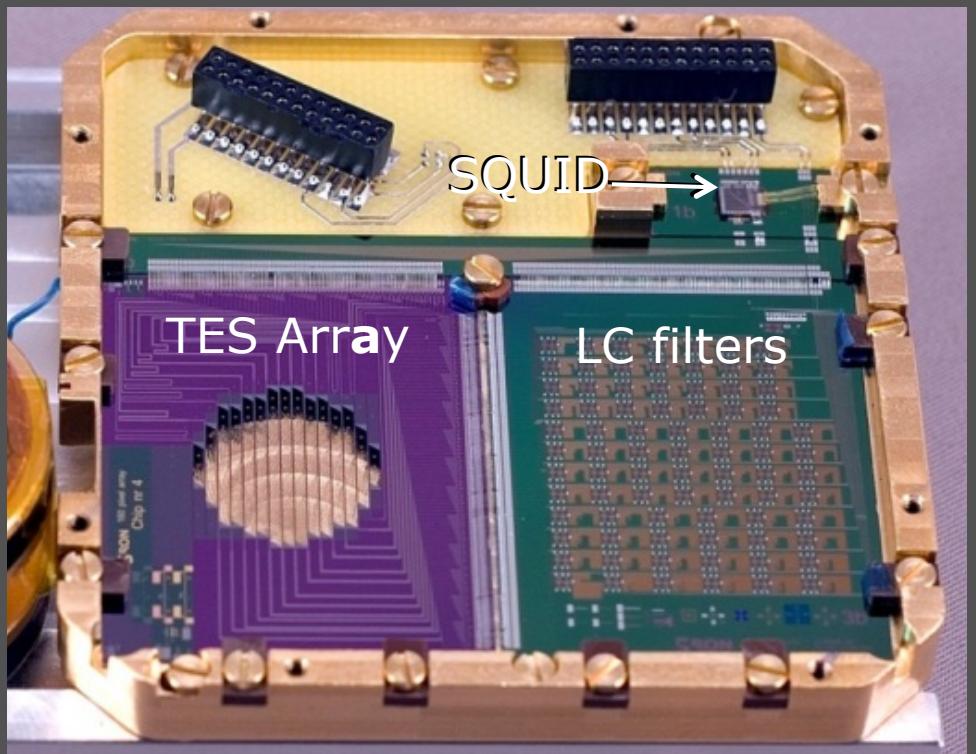
- Work is largely driven by developments for SPICA
 - SRON/Cambridge – Low NEP $\sim 3 \times 10^{-19} \text{ W}/\sqrt{\text{Hz}}$, (Freq multiplexed TES)
 - JPL - $1 \times 10^{-19} \text{ W}/\sqrt{\text{Hz}}$ (TES)
- Delft/SRON $3.5 \times 10^{-19} \text{ W}/\sqrt{\text{Hz}}$ (optical) Al MKID
 - Nice demo of photon noise
- Thermal conductance control – metamaterials
 - Allows development of stop band structures to limit conduction.
- TES physics

SAFARI FDM demonstrator



68 pixel experiment successful

- NEP: $1.1 \times 10^{-18} \text{ W}/\sqrt{\text{Hz}}$
- $f_0 = 1160 - 3218 \text{ kHz}$, $\Delta f = 28 \text{ kHz}$
- Successful read out of 41 pixels

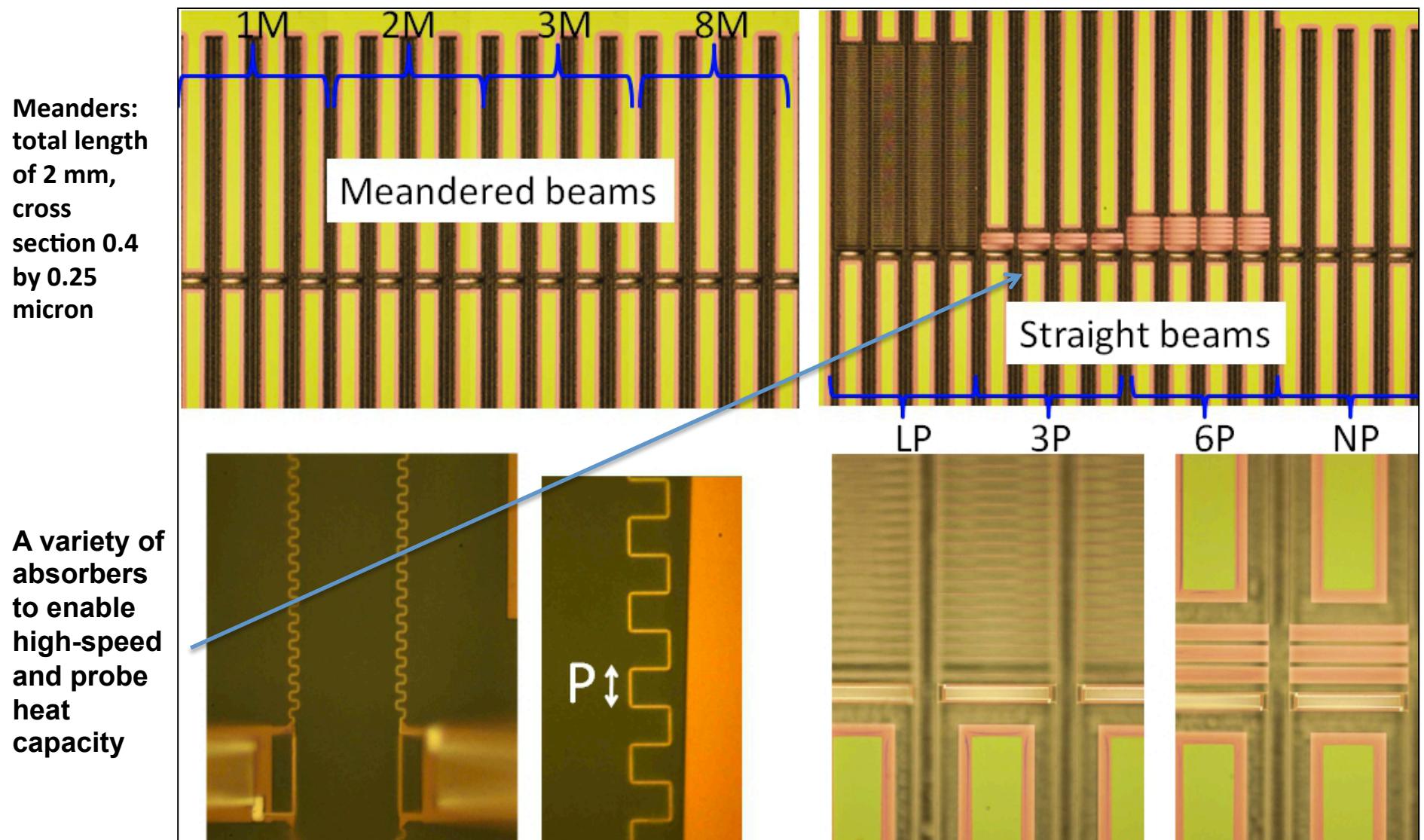


160 pixel experiment in progress

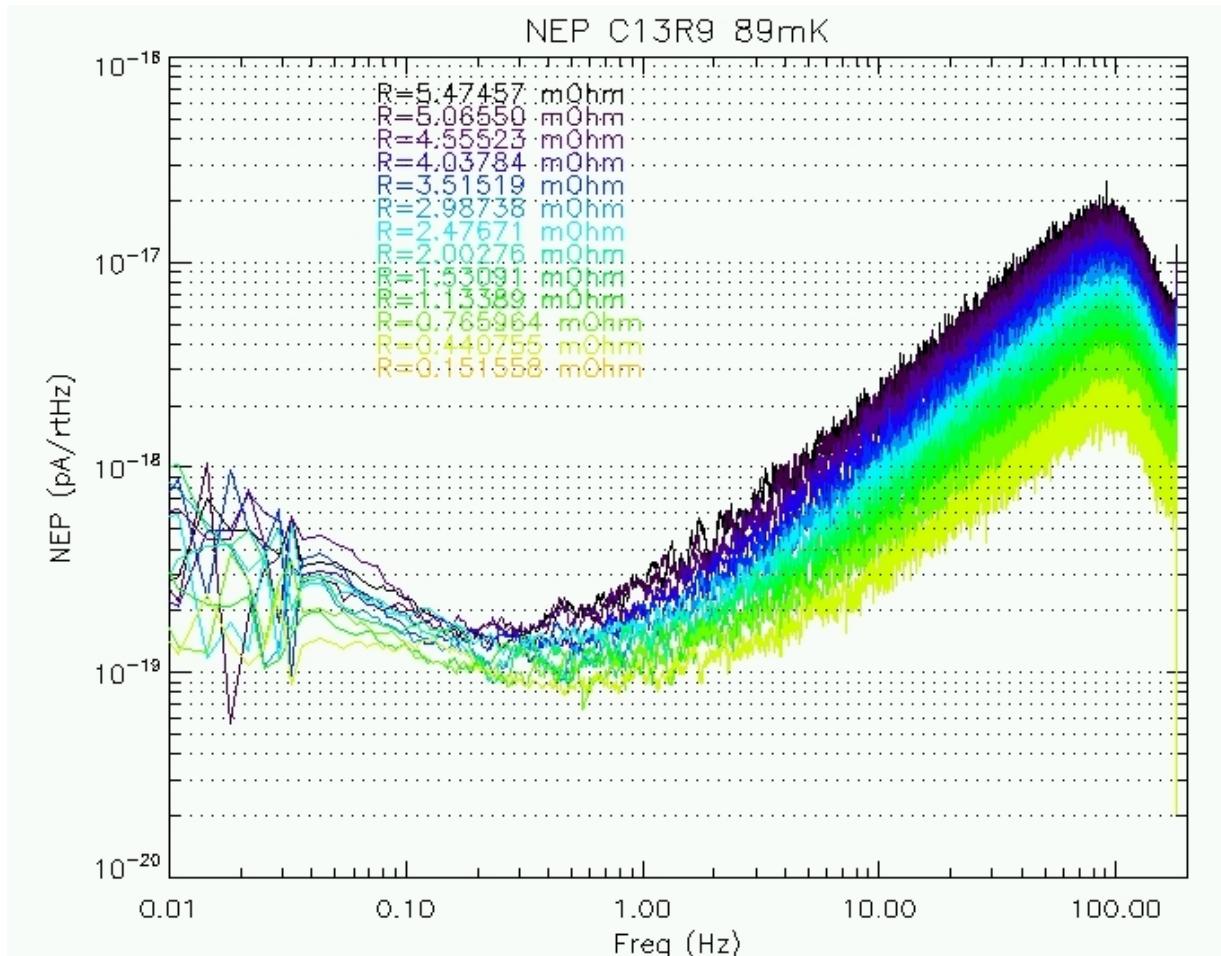
- NEP: $8 \times 10^{-19} \text{ W}/\sqrt{\text{Hz}}$
- $f_0 = 1200 - 3600 \text{ kHz}$, $\Delta f = 14 \text{ kHz}$
- Successful read out individual pixels
- Crosstalk issues understood,
- Solving crosstalk for simultaneous read-out

BLISS prototype TES arrays

long SiN beams, 60 mK MoCu bilayer thermistors



BLISS TES Bolometers -- Performance



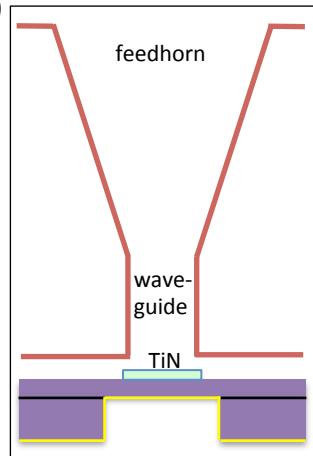
- Meeting electrical NEP requirement of $1e-19$ W / $\sqrt{\text{Hz}}$ w/ time-domain MUX
- Lower NEPs in reach, requires improved filtration.
- Have discovered anomalous excess heat capacity in **mesh** devices: $\sim 10x$ relative to pure nitride
 - residue on edges related to our XeF_2 processing
 - solutions under study: etch nitride first, then clean (e.g. BOE) prior to metal layers.

Need more bandwidth to deal with cosmic rays – must eliminate excess heat capacity

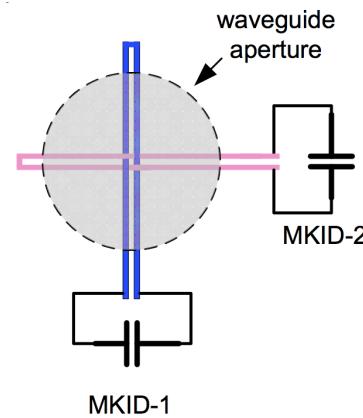
Photon-noise limited sensitivity in MKIDs at 250 μm

in development for next-generation BLASTPol

Feedhorn-coupled
 MKID concept

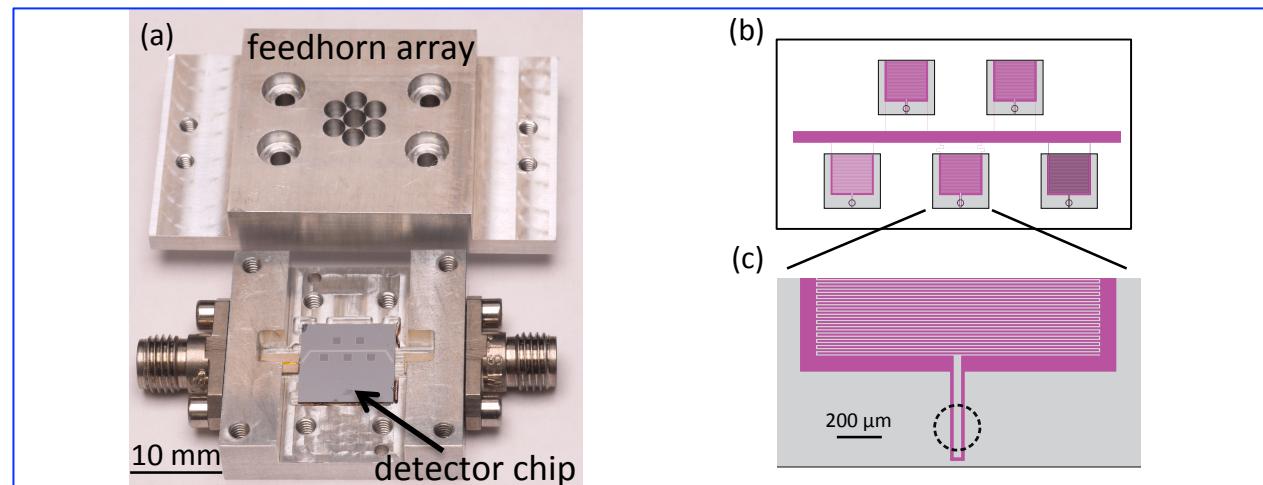


dual-polarization sensitivity
 within one spatial pixel

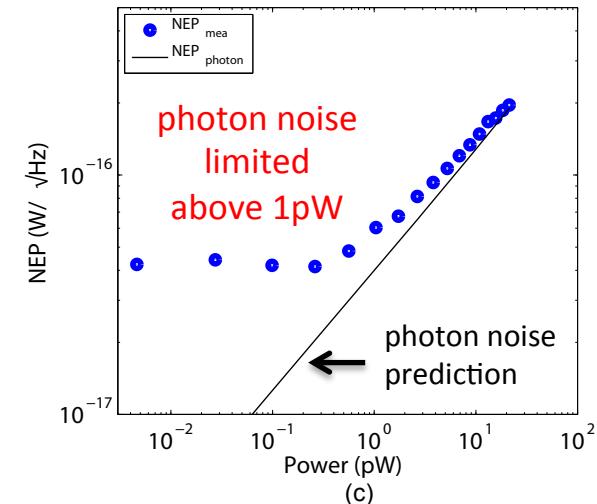
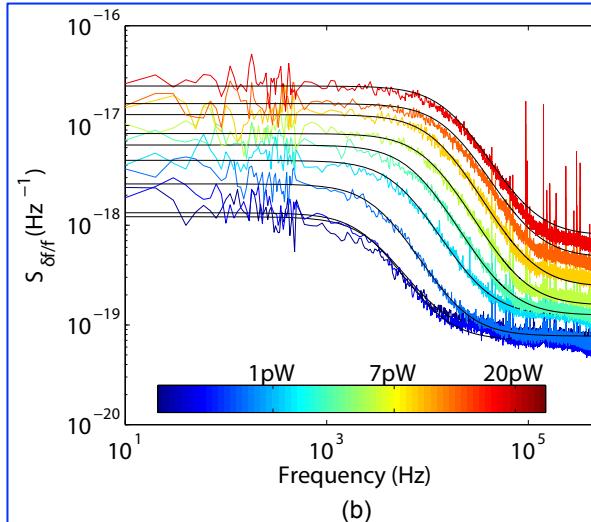


detector development is a collaboration between NIST, UPENN, ASU and Stanford

Experimental package

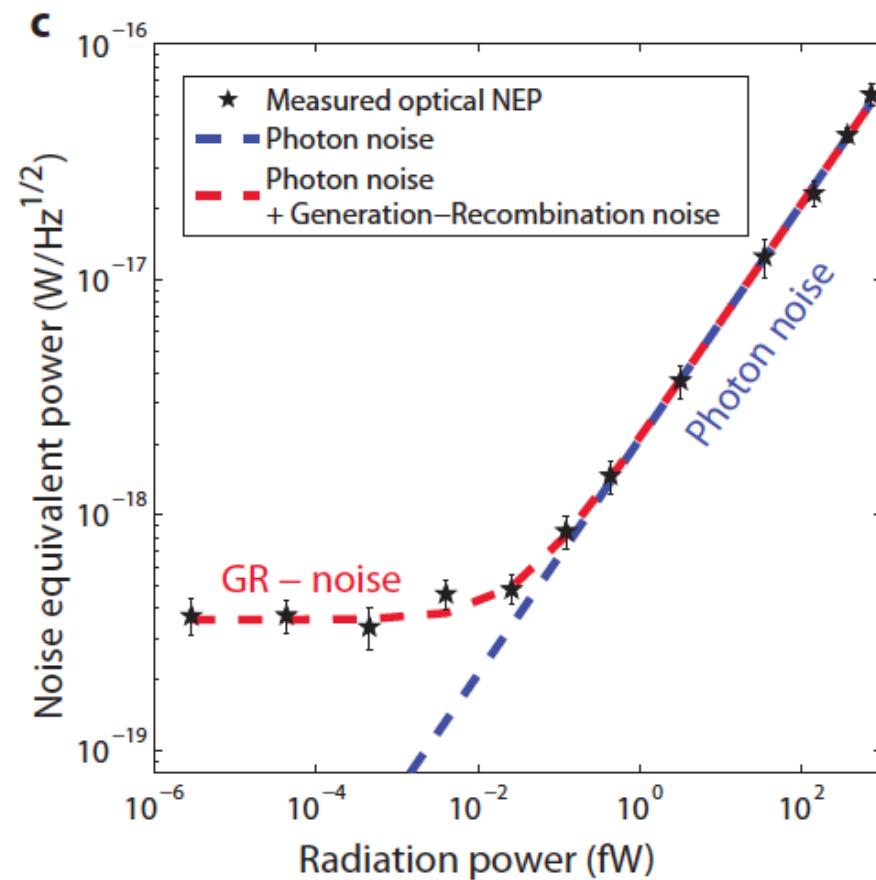
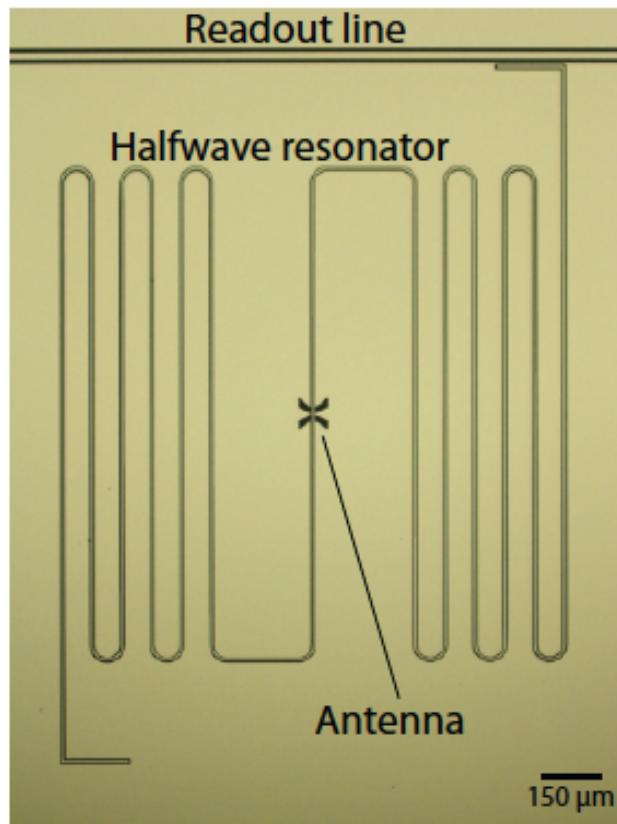


Sensitivity to variable temperature thermal load



KID limit: NEP @ 1.55 THz

Limited only by fluctuations in Quasiparticle number or photons
Amplitude readout only!



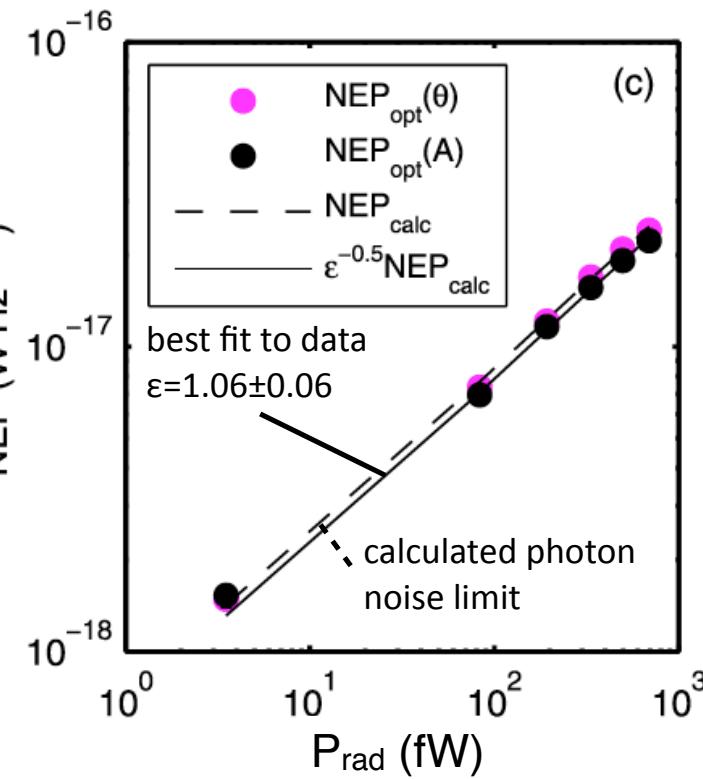
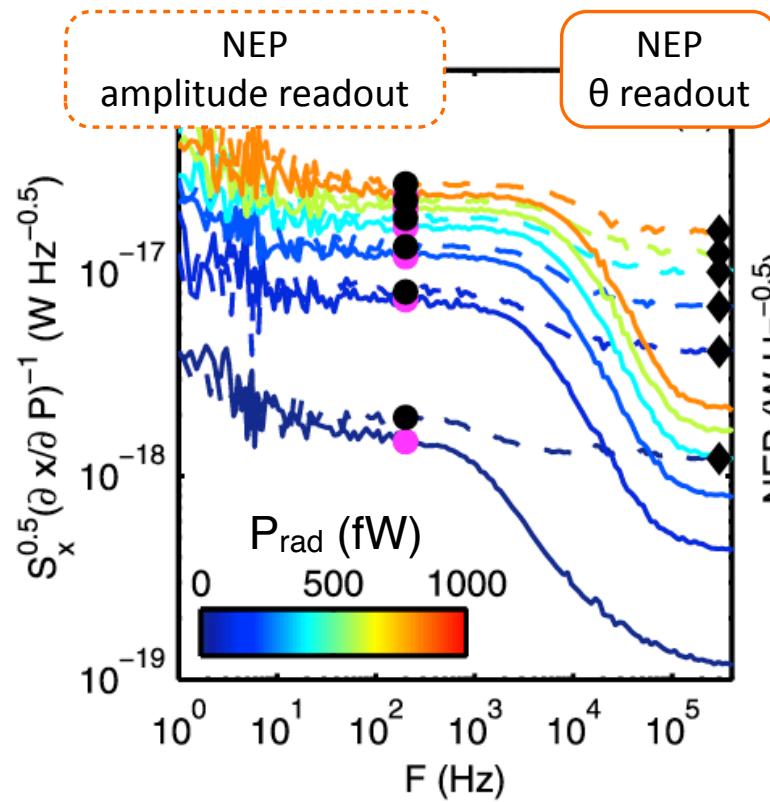
P. J. de Visser, J. J. A. Baselmans, J. Bueno, N. Llombart, and T. M. Klapwijk,
Nature Communications, vol. 5, pp. 1–8, Feb. 2014.

Photon noise limit using Phase Readout: 350 GHz

Photon Noise limited θ and \mathbf{A}

Aperture efficiency 75%

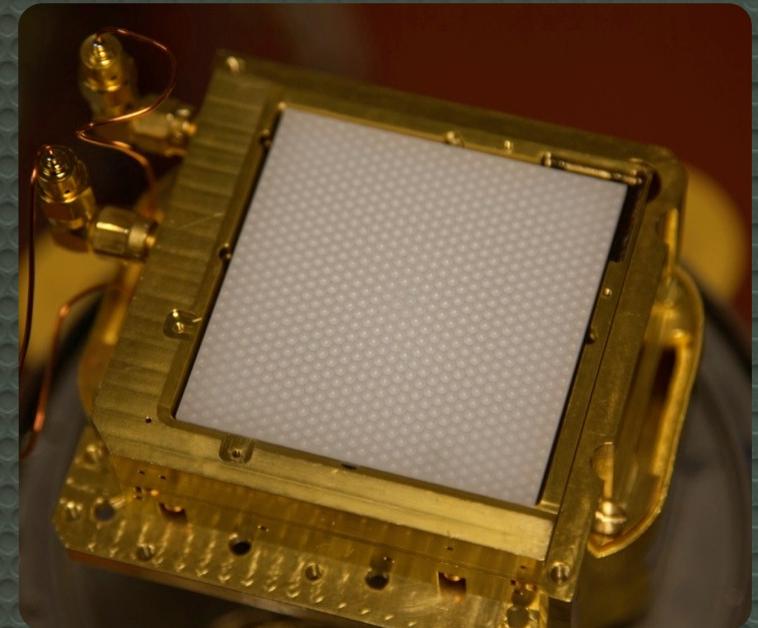
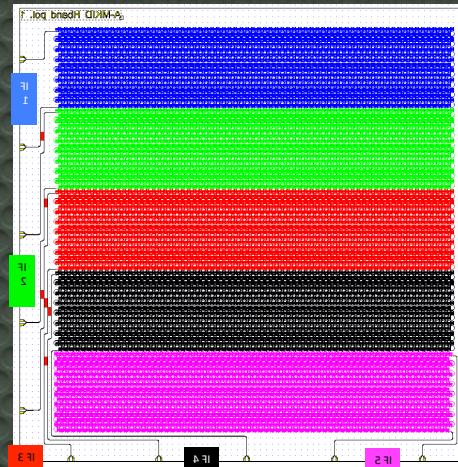
$$\text{NEP}_{\text{photon}} = \sqrt{\frac{2P_{\text{rad}}hF(1 + \eta_{\text{opt}}B) + 2\Delta P_{\text{rad}}/\eta_{\text{pb}}}{\eta_{\text{opt}}}}$$



Arrays for A-MKID

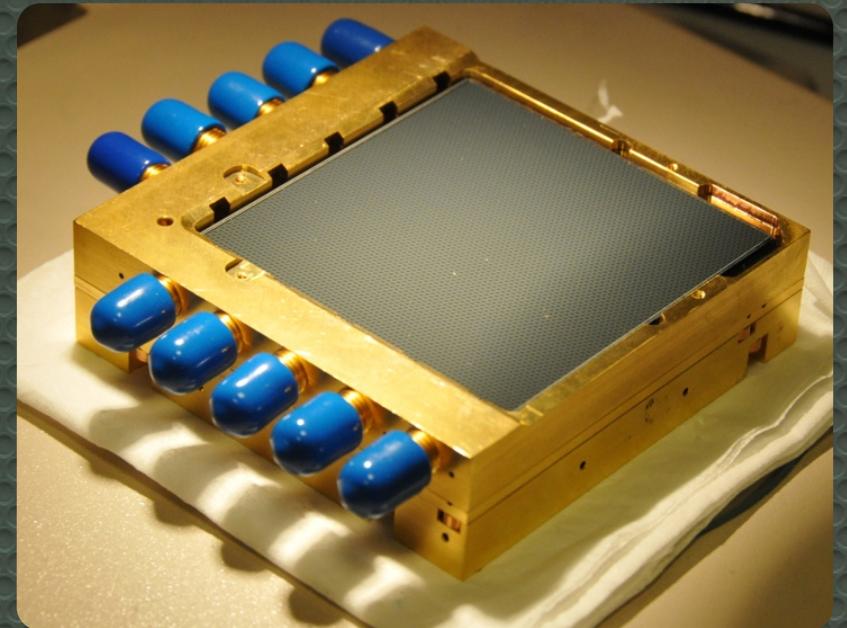
350 GHz
1 IF line
62.5 x 62.5 mm
880 pixels
 Al_2O_3 lens array 2 mm

850 GHz
5 IF lines
62.5 x 62.5 mm
5400 pixels
Si lens array 0.8 mm



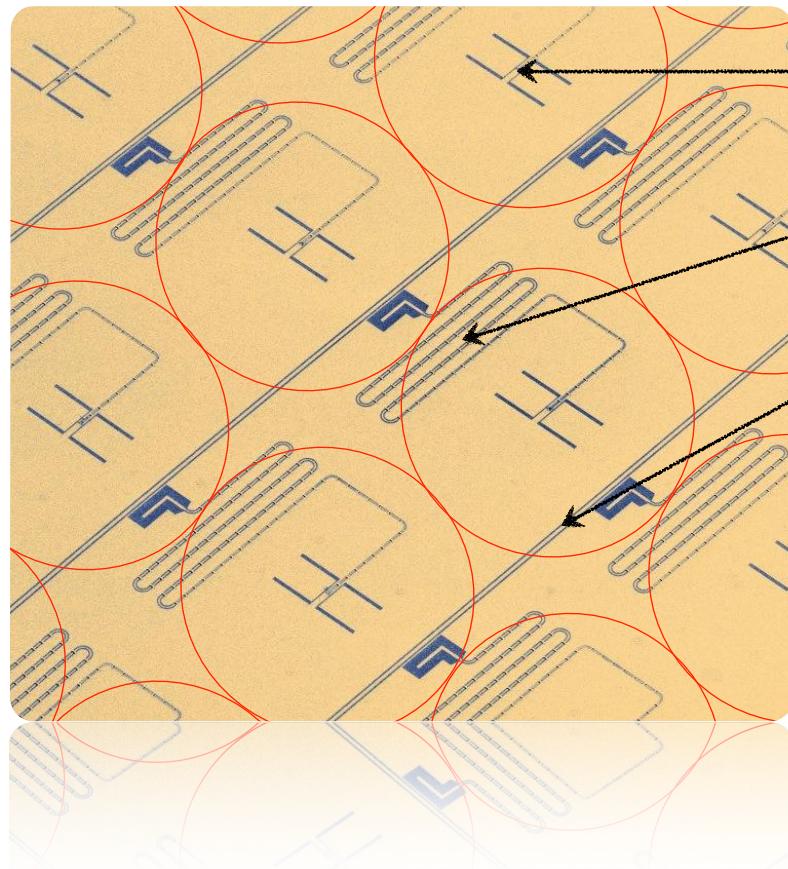
ceratec®
Technical Ceramics BV

PHILIPS
Philips Lighting Uden



veldlaser
laser micro machining materials

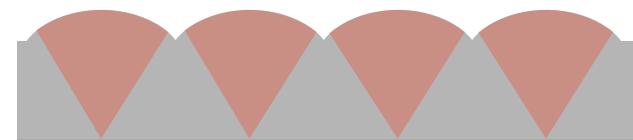
KID imaging Array



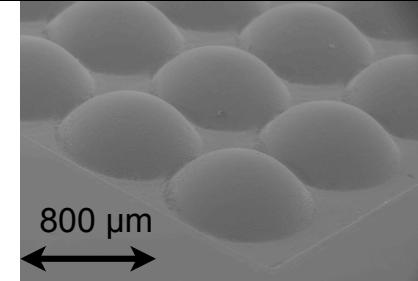
Identical antenna's

Resonators have different length
Different resonance frequencies

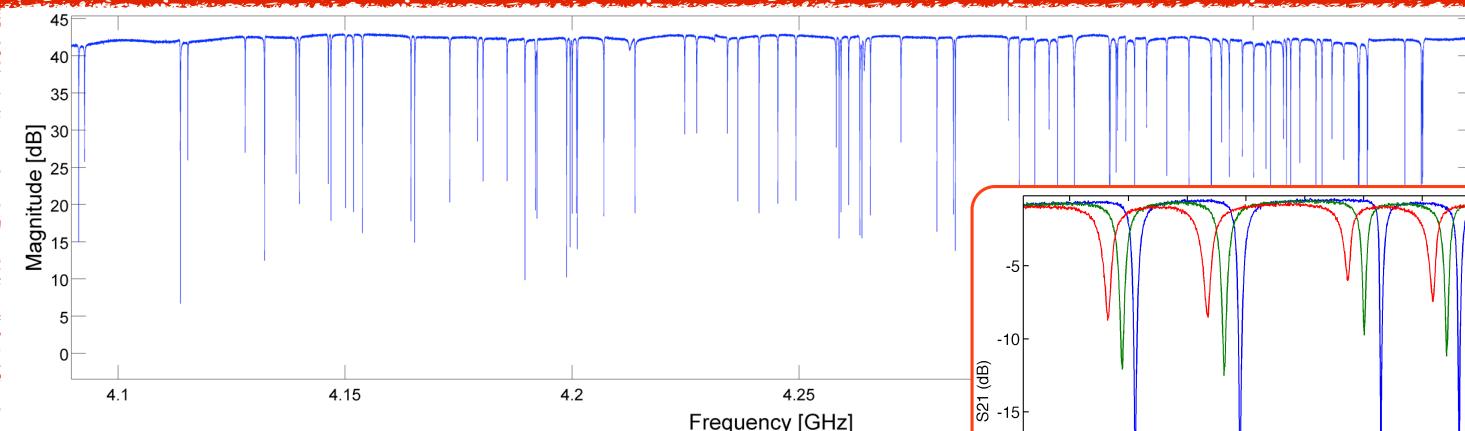
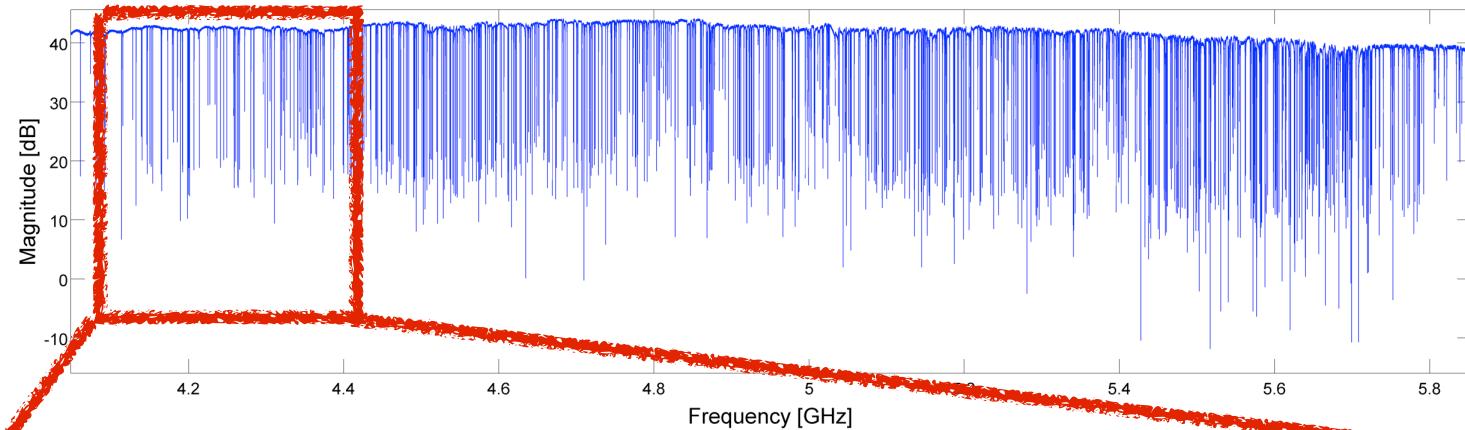
1 readout line connecting all pixels



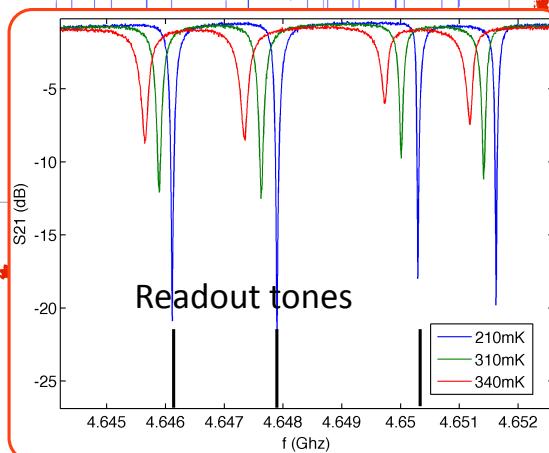
Flies eye lens array, 1 lens/pixel



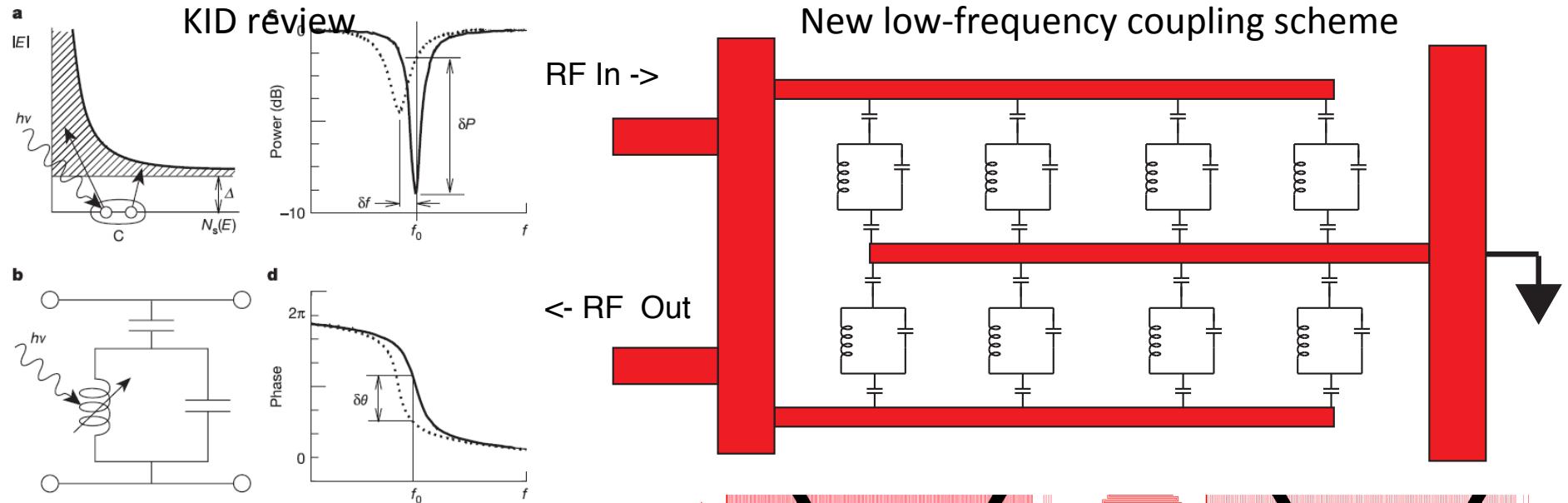
Readout: each dip = 1 KID



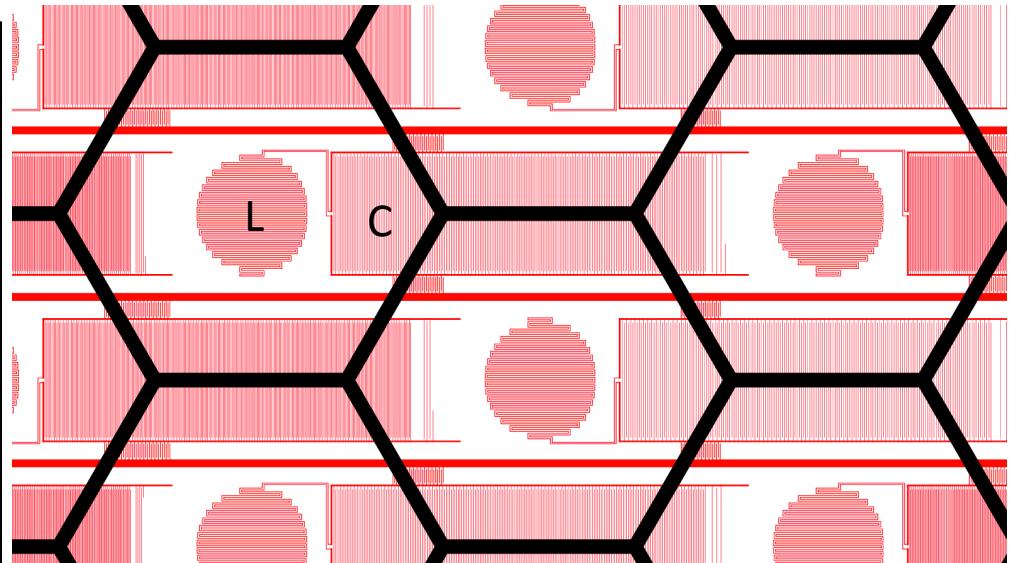
1000-10.000 pixels/coax cable pair



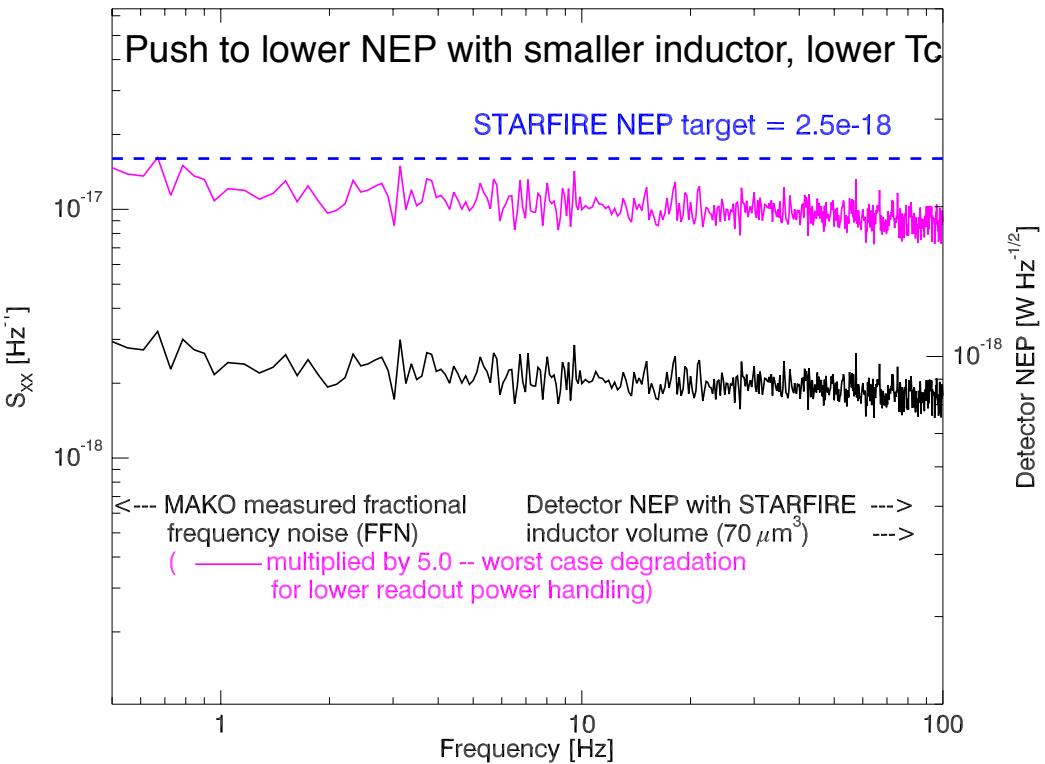
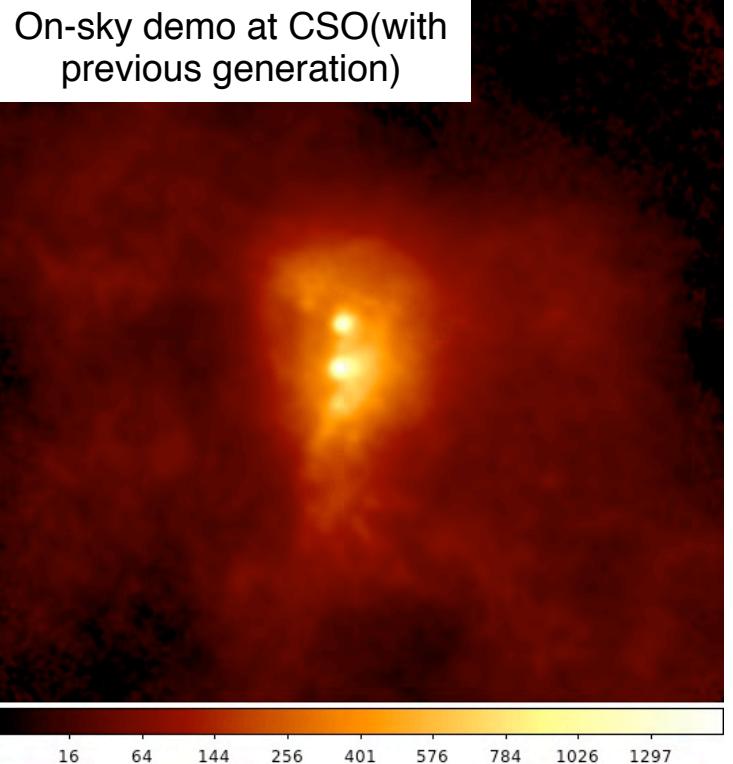
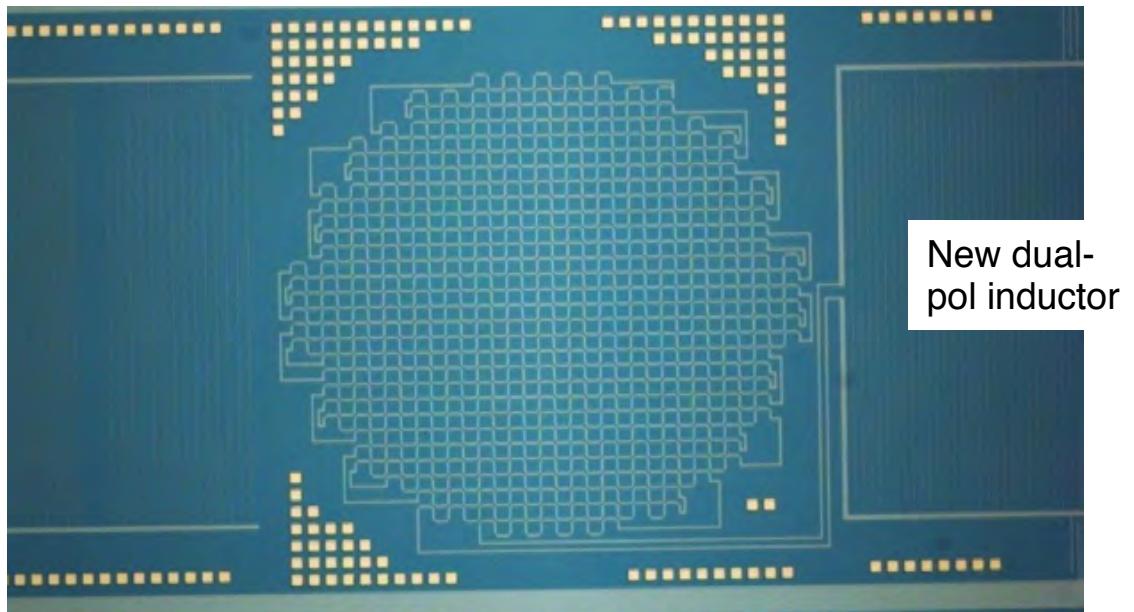
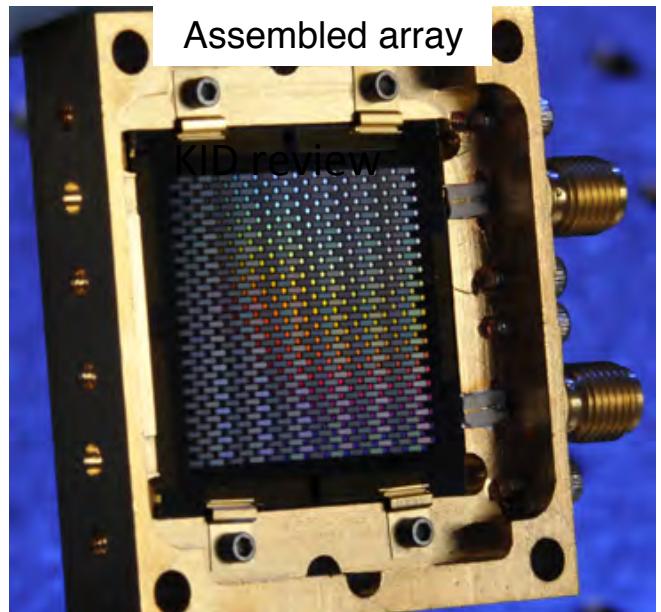
Caltech / JPL Titanium-Nitride KIDs



- Using low readout frequencies (~100 MHz)
 - Eliminates mixing / downconverting
 - At 100 MHz, wavelength is very large (~ 800 mm in Si)
 - Can avoid transmission line and just use lumped element model -> interdigitated capacitor coupling scheme.
- Simple single layer TiN fabrication. Note tuning tines on right side of capacitors.
- Smaller inductor – uses lens coupling.
- Will be used for CCAT SWCam.



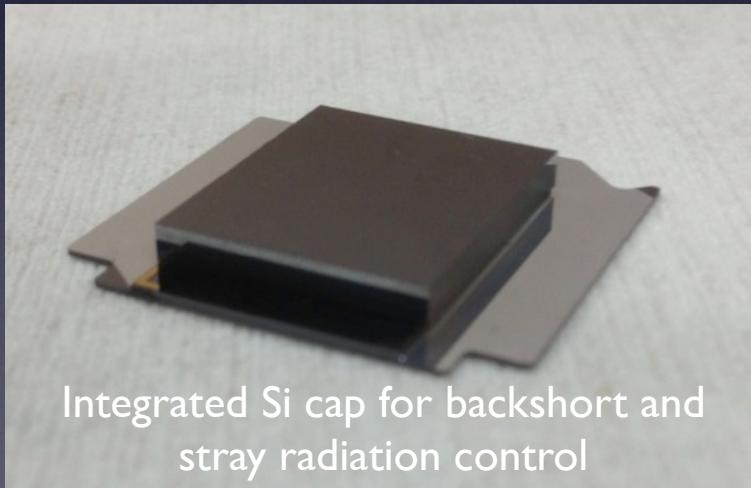
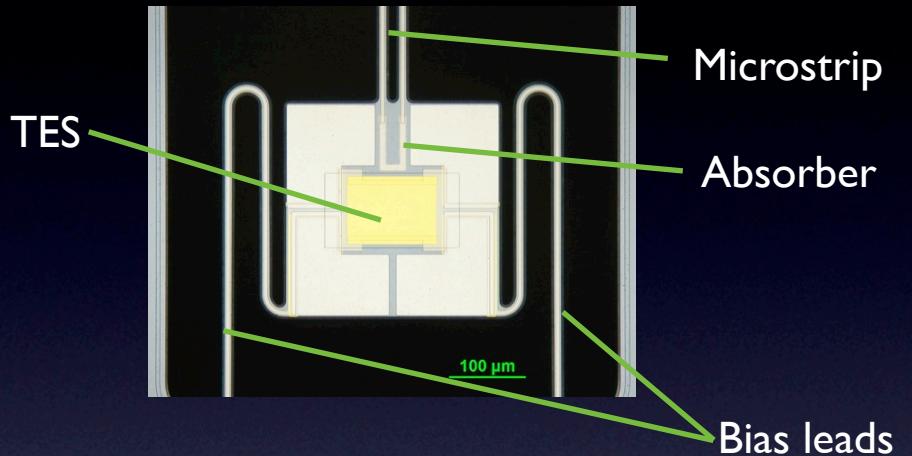
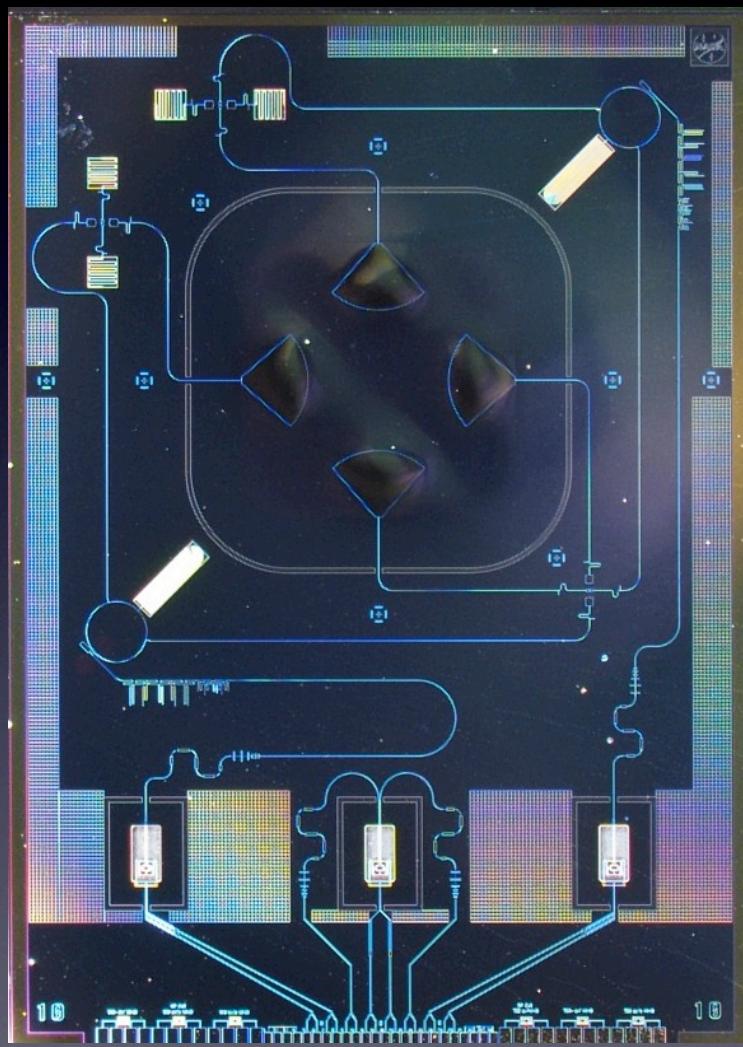
Hexagonal optical lattice, 1 mm pixels



Integrating Instrument Functions

- Integration and test is often the most expensive phase of development of an instrument
 - First introduction of complex subsystems in a difficult environment
 - Detectors which integrate instrument functions are very appealing – all these interfaces are well tested at the subsystem level.
 - Significant levels of instrument integration will be widely used in the future
 - Work is in early phases, but proceeding well
 - μ -Spec , SuperSpec
 - Matt will review progress.

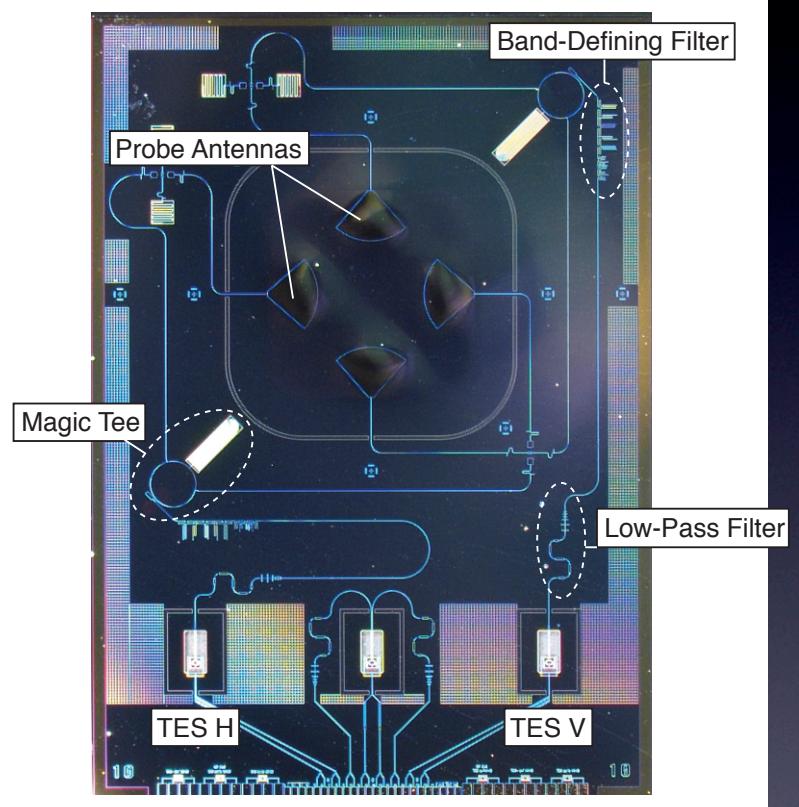
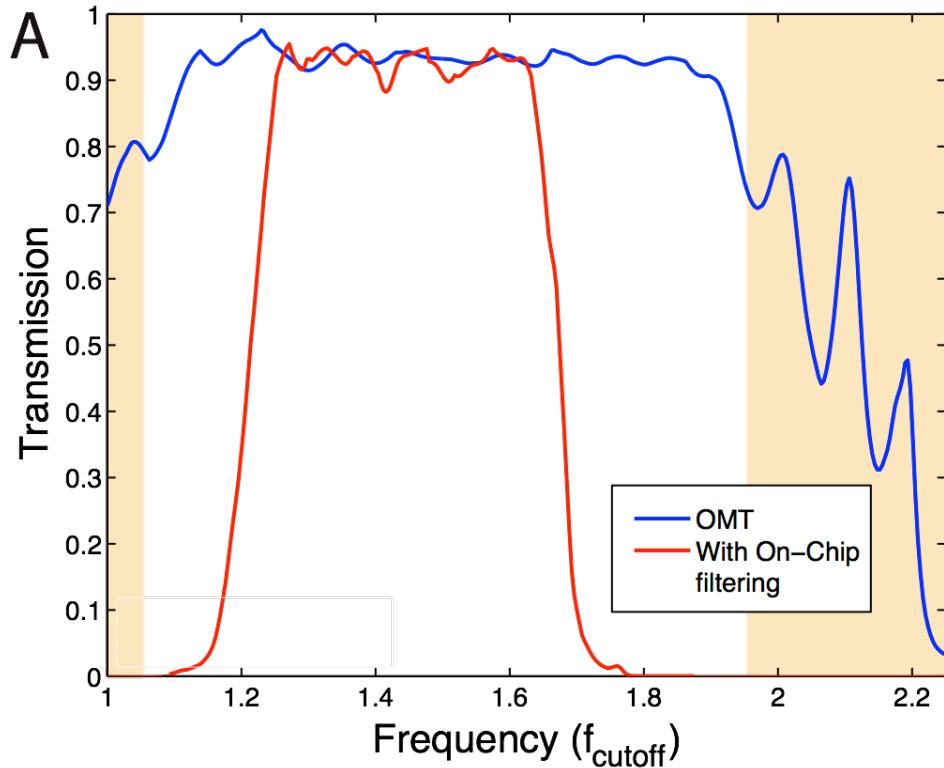
40 GHz Detector Chip



Integrated Si cap for backshort and
stray radiation control

Crowe et al. (2012)
Wollack et al., in prep

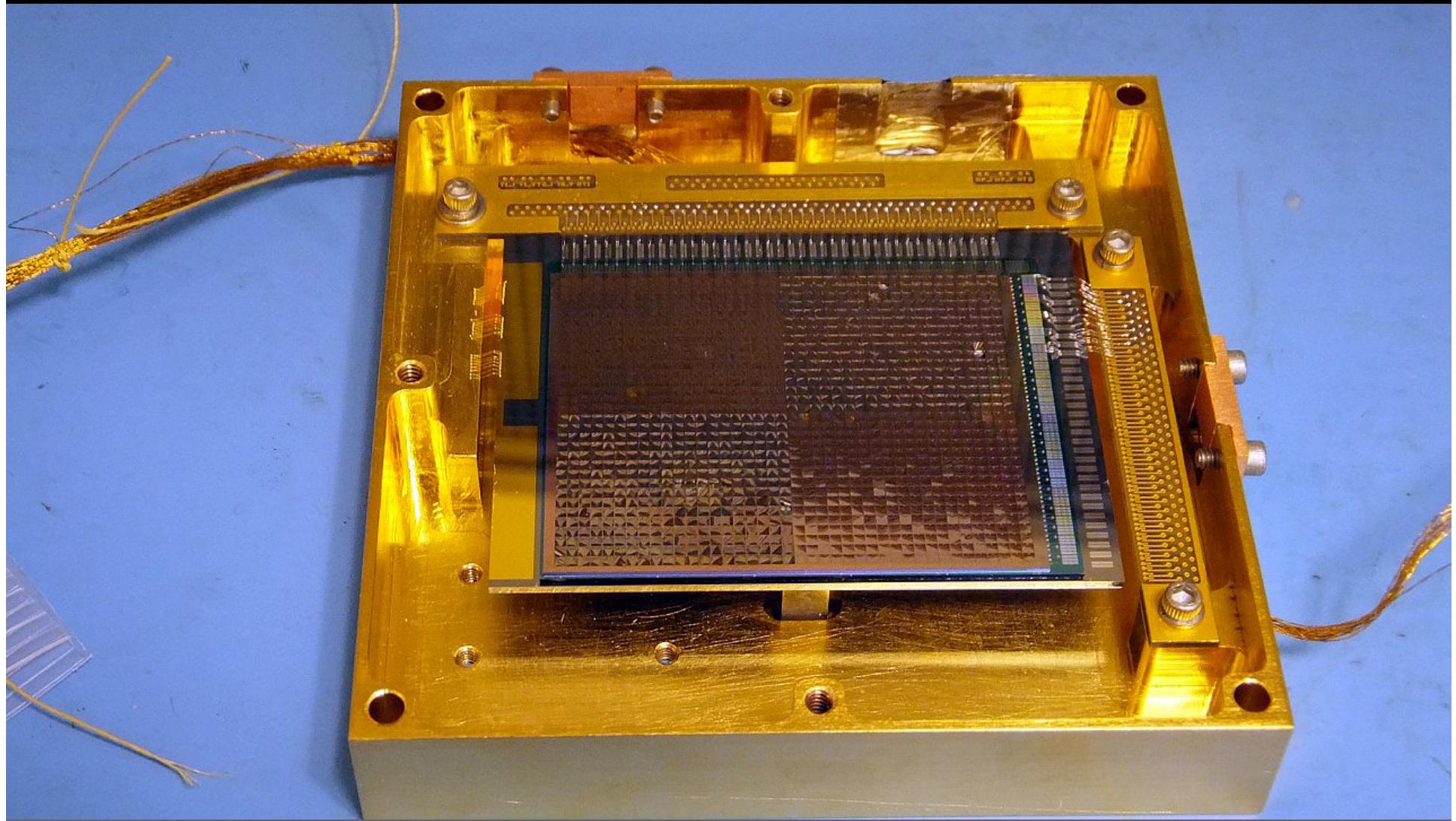
40 GHz Frequency Response



- Symmetric OMT has wide intrinsic bandwidth
- Filtering scheme inherently flexible

U-Yen et al. (2007, 2008, 2009)
U-Yen & Wollack (2008)

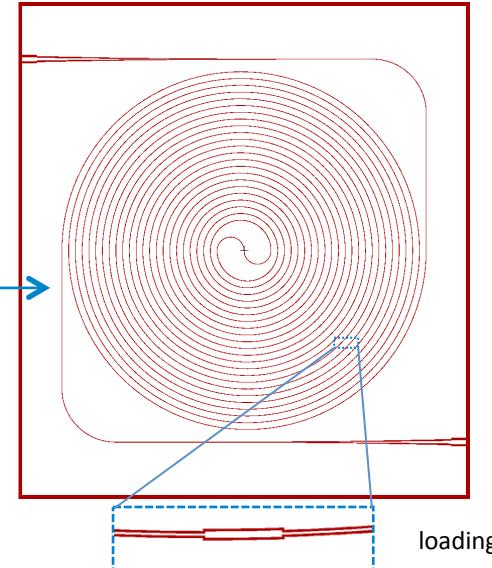
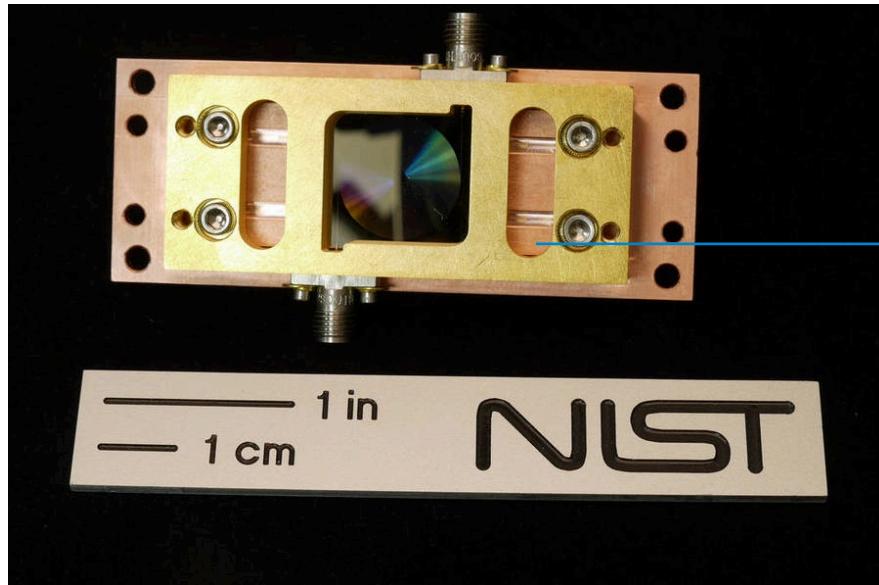
SOFIA HAWC BUG TES on 32 x 40 NIST MUX



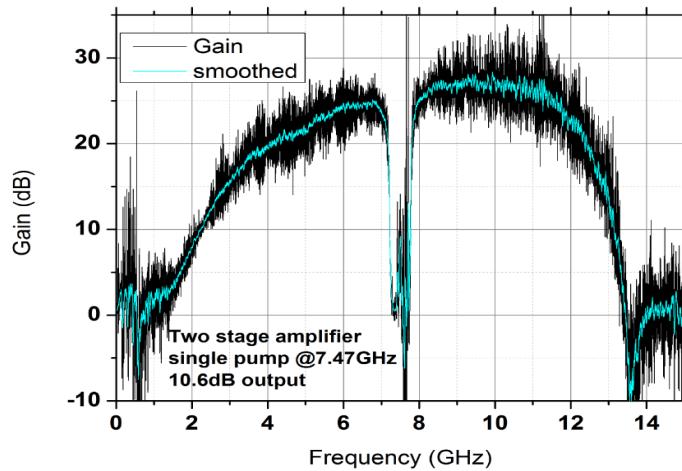
Amplifiers – The Wild Card

- There has been rapid progress in the development of parametric amplifiers based on the current dependence of kinetic inductance.
 - Zmuidzinas group 2012.
 - The quantum-limited noise temperature of a 1 GHz amplifier is ~ 25 mK.
 - Reasonable path to SMM single photon detection
 - Path to whole range of resonator-based detectors, even using a dissipation readout.
 - Dynamic range?

Kinetic Inductance Traveling-wave Parametric Amplifier (KIT)



2m-long coplanar waveguide (CPW) made of 20nm NbTiN on 2cm x 2cm Si chip with periodic impedance loadings



- Proposed and first demonstrated by Caltech/JPL in 2012 (Eom et al., Nature 8, 2012).
- Funded by NASA and ARO, NIST is collaborating with Caltech/JPL, Stanford, Goddard, BBN to develop KIT amplifier for detector and Qubit readout.
- NIST KIT current status:
 - >15 dB gain over 2GHz of bandwidth (single-sided) by one KIT or >20 dB gain over 4GHz by cascading 2 KITs.
 - Measured system noise $T_n \sim 2$ K, a factor of ~ 2 better than HEMT but much higher than quantum limit.
 - Severe chip heating is likely to cause the added noise.

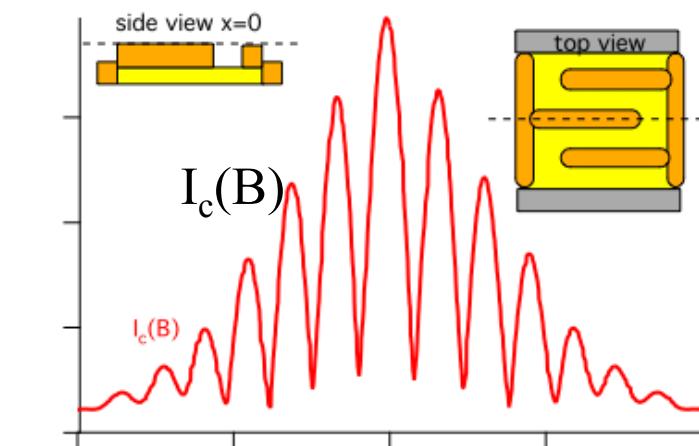
Interesting Developments

- TES Physics – Excellent progress has been made in understanding the TES in some regimes.
 - Sadleir et al. have developed techniques to tailor both α and β across the transition, and even create negative β .
 - Find the TES devices behave as fully coherent systems, showing STJ behaviors
- Engineering of thermal conductance
 - Understanding surface scattering
 - Phononic band gaps
- Coherent Receiver Progress

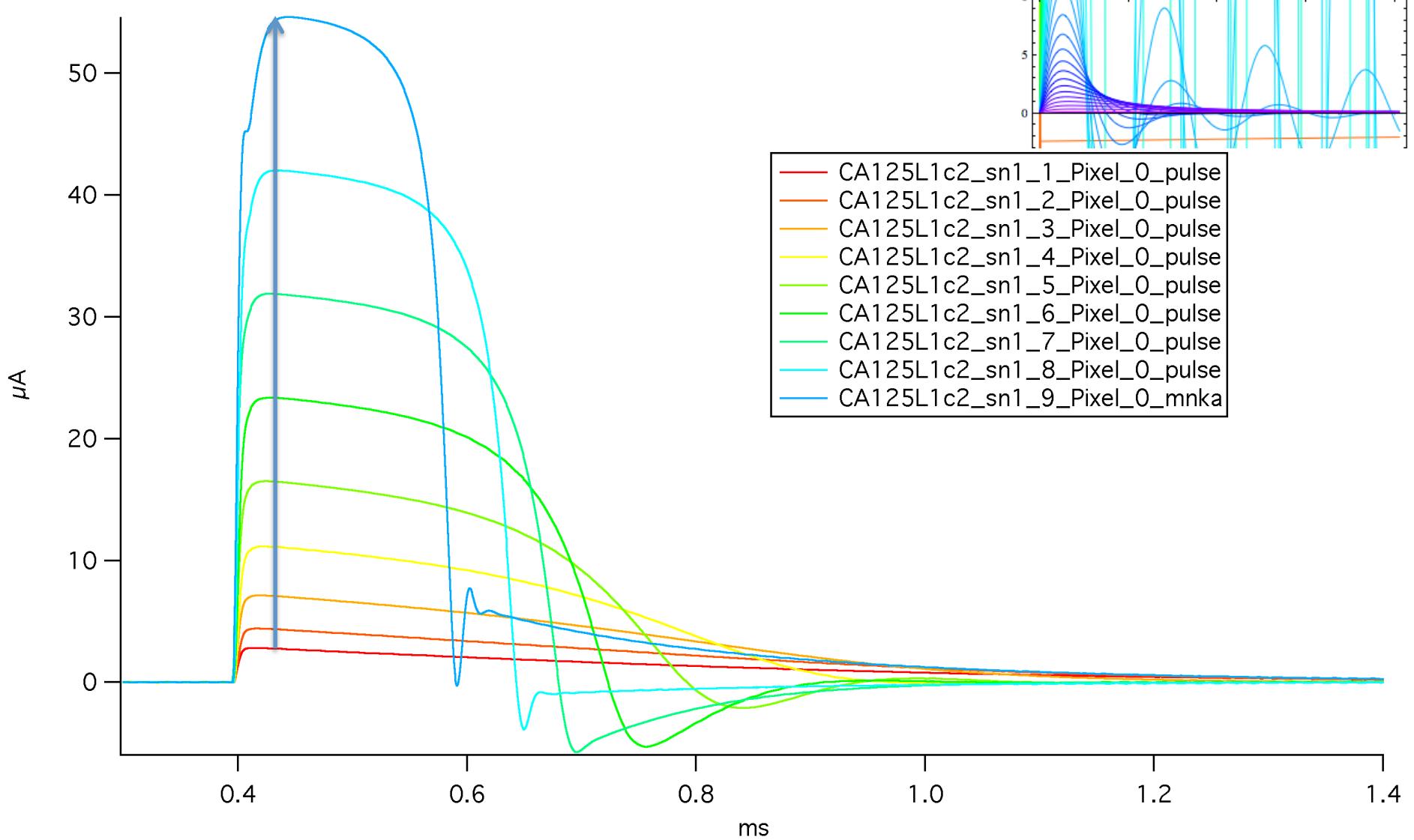
		SC Weak Link GL model	vs	Uniform SC
<i>R transition width size and L scaling</i>	$\Delta T _I(L)$	$\sim mK$ ✓ $\sim L^{-2}$ ✓ (GL model)	$\sim \mu K$ MT AL fluctuations $\sim nK$ KT theory L independent	
<i>Effective transition temperature</i>	$T_c _I(L)$	$\sim L^{-2}$ ✓ (GL model)	L independent	
<i>Critical current temperature and L dependence</i>	$I_c(T,L)$	Exponential ✓ $\sim \text{Exp}[-L \sqrt{T}]$ (GL model $T < T_{ci}$)	Power Law 3/2 power (thin film)	
I_c magnetic field dependence	$I_c(B)$	Oscillations with $ B $ (Josephson Effect) ✓	Monotonic decreasing with $ B $	

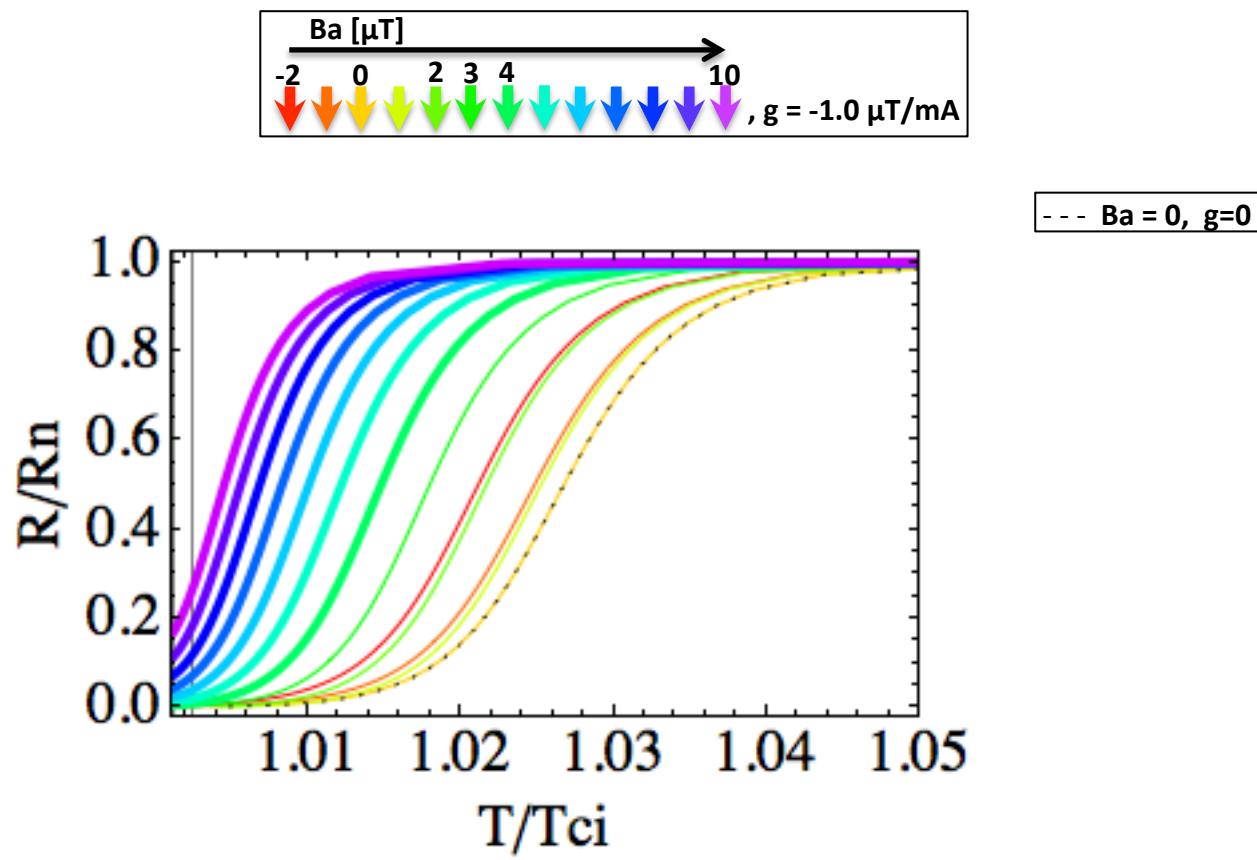
Range of Measurements

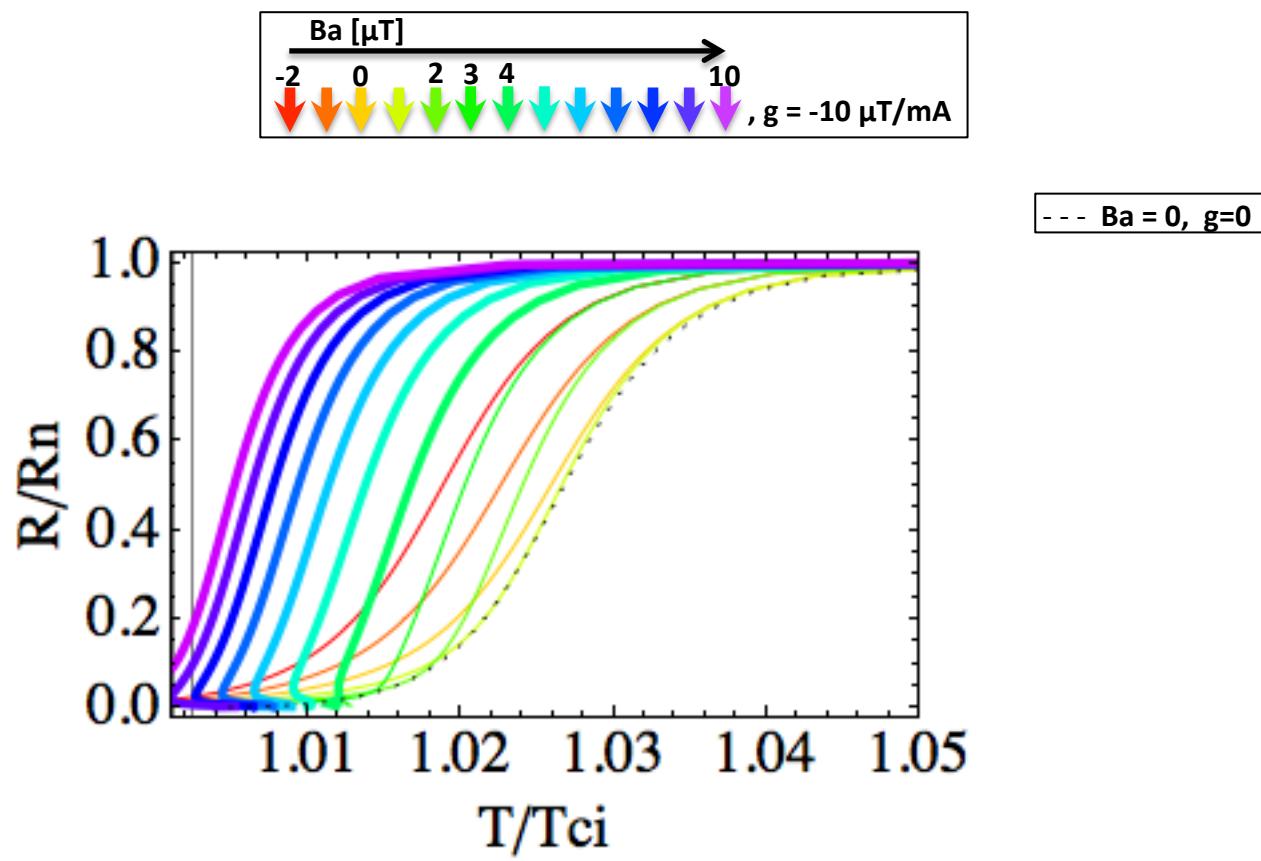
R: small current (~ 50 nA) excitation
 AC measurements
 I_c : over 7 decades
 L: 8 to 290 μm
 s: 2.3 to 130 μm
 T: 40 mK to 1 K
 B: 0 to 0.5 mT

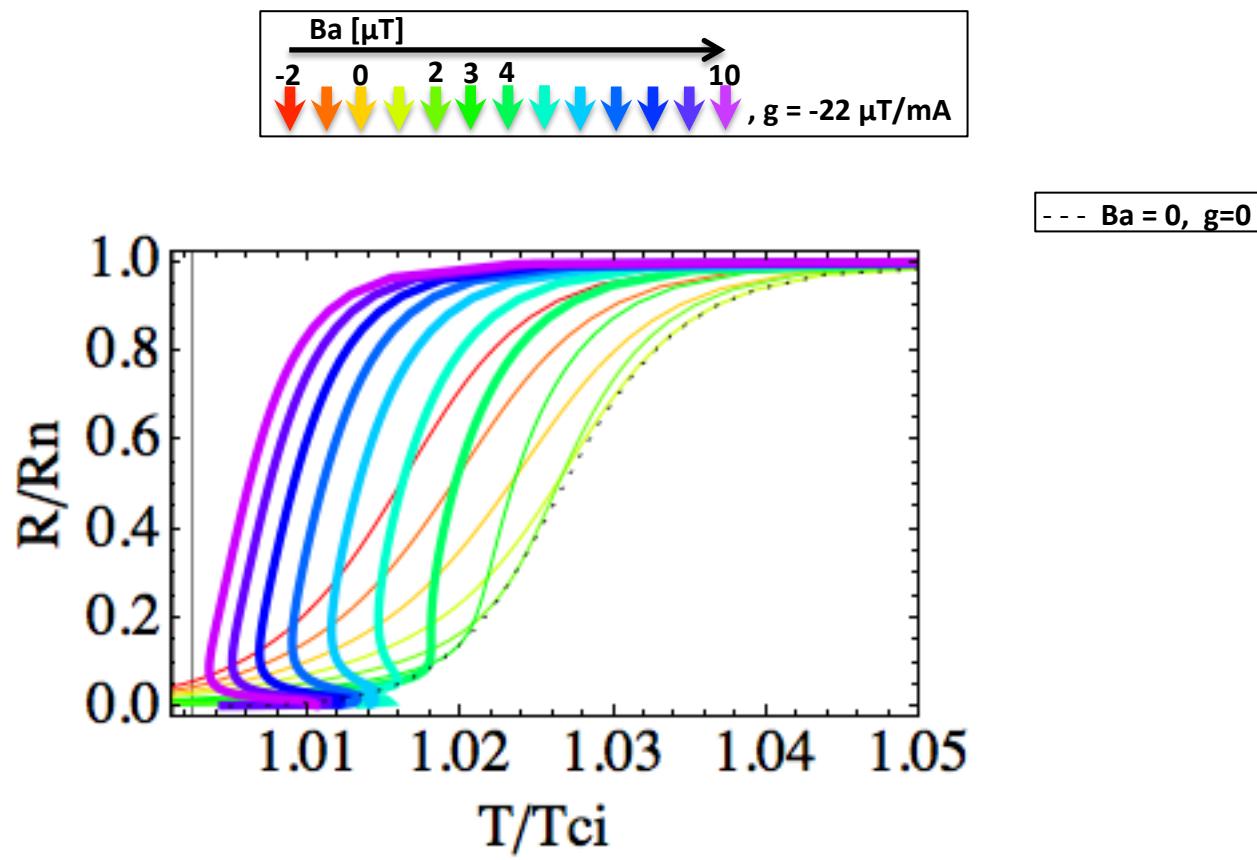


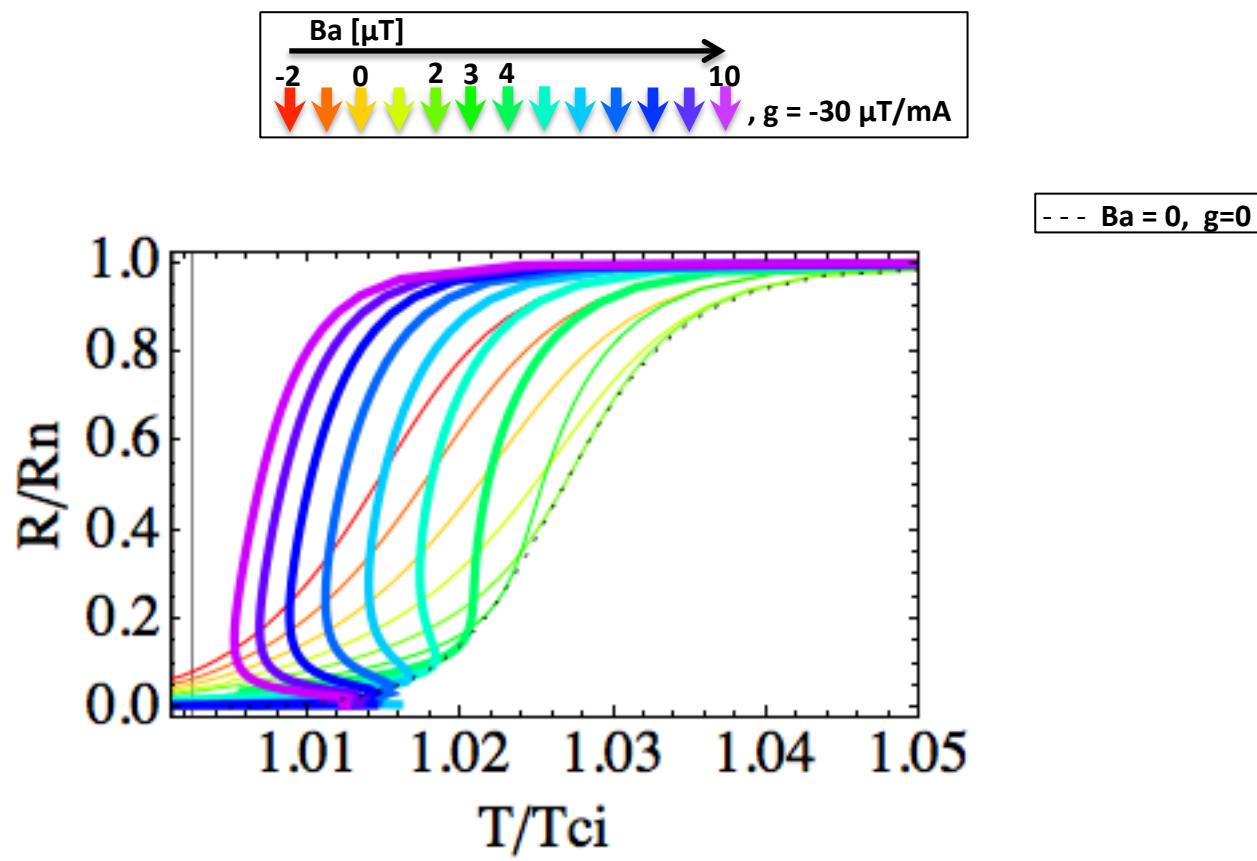
Magnetic Tuning Increasing Signal Size until saturation

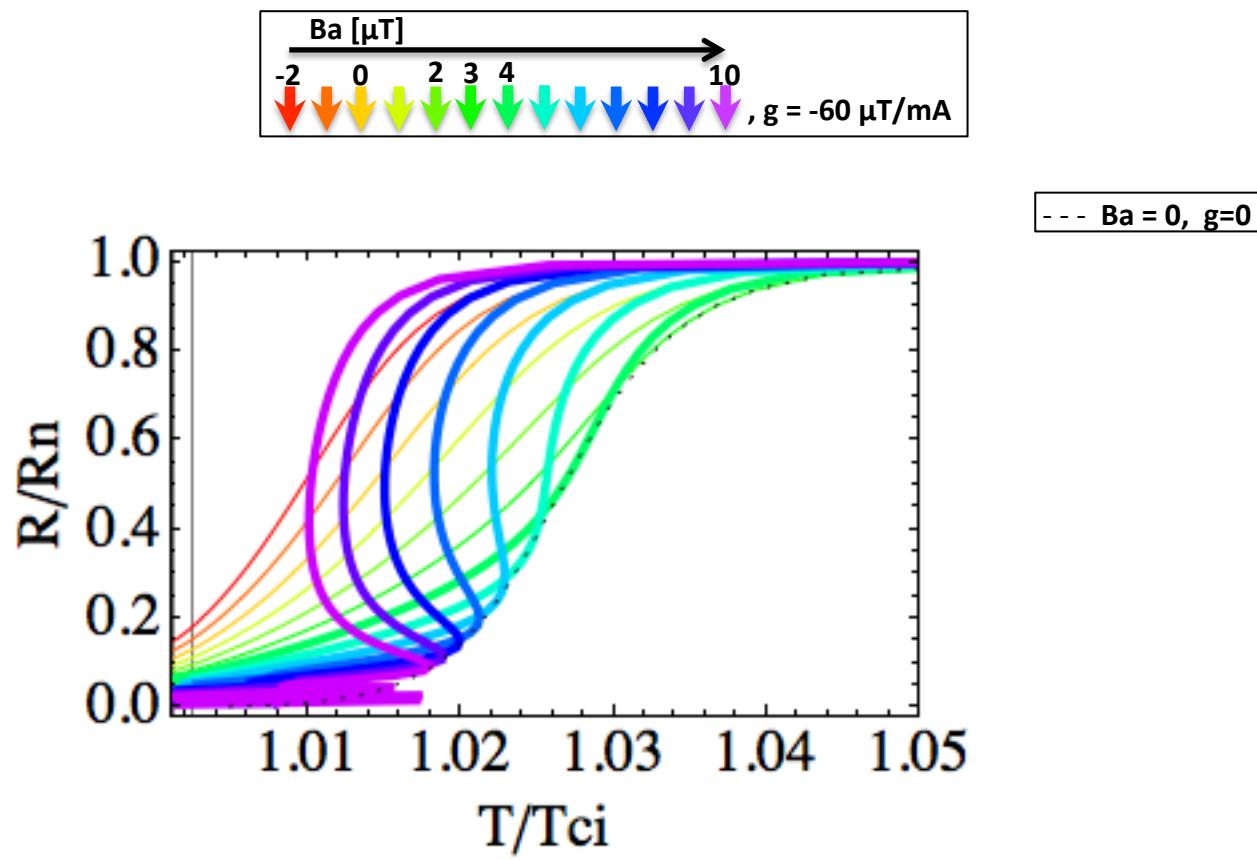


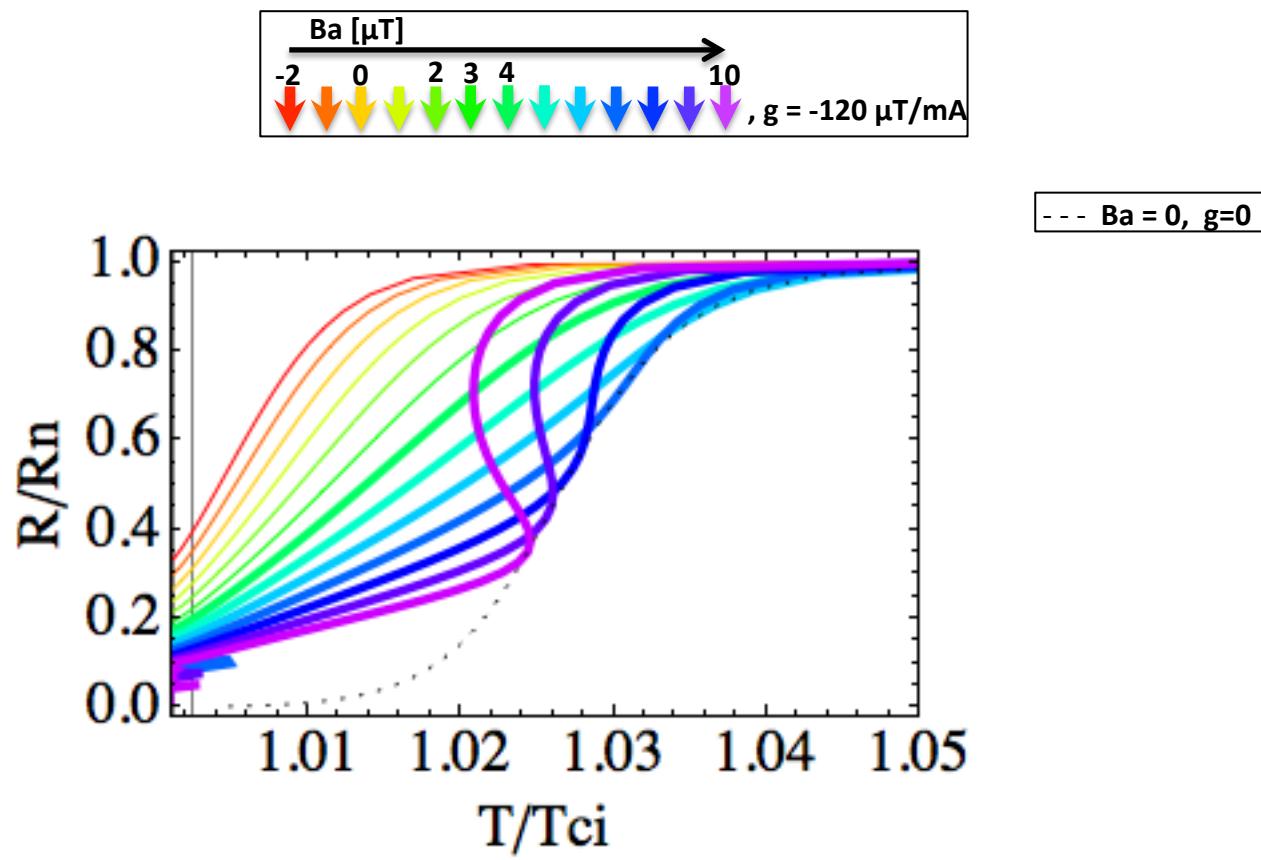


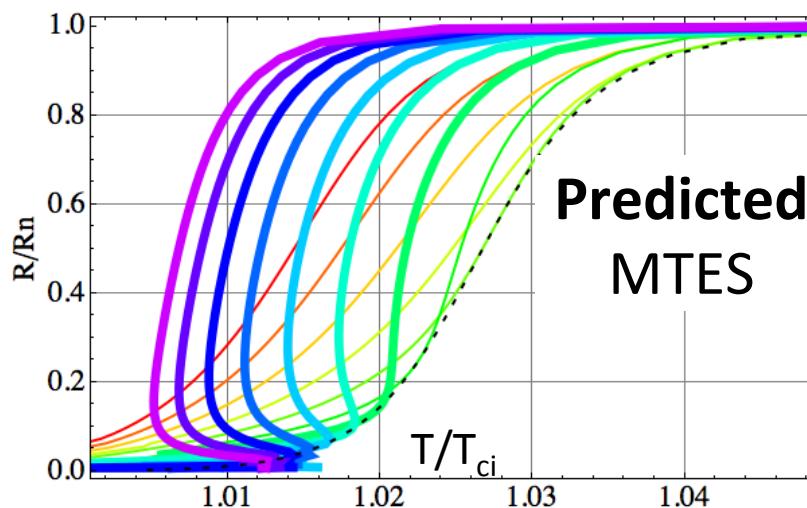
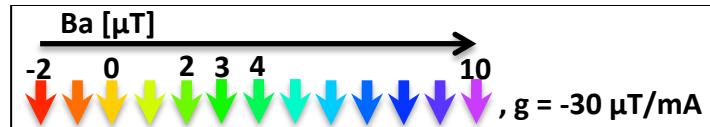






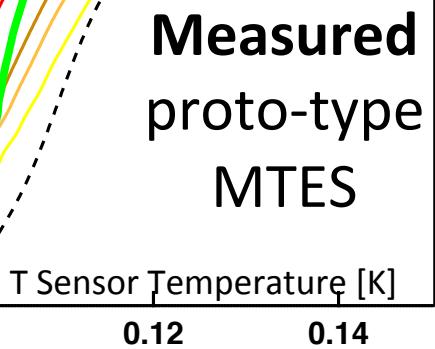




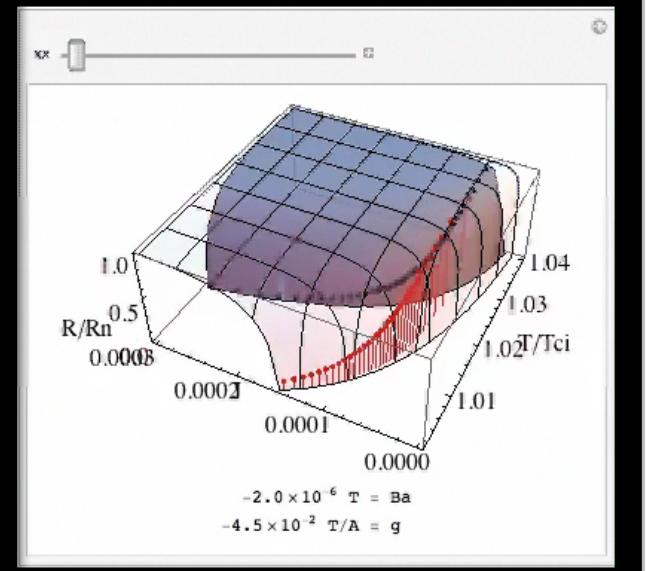
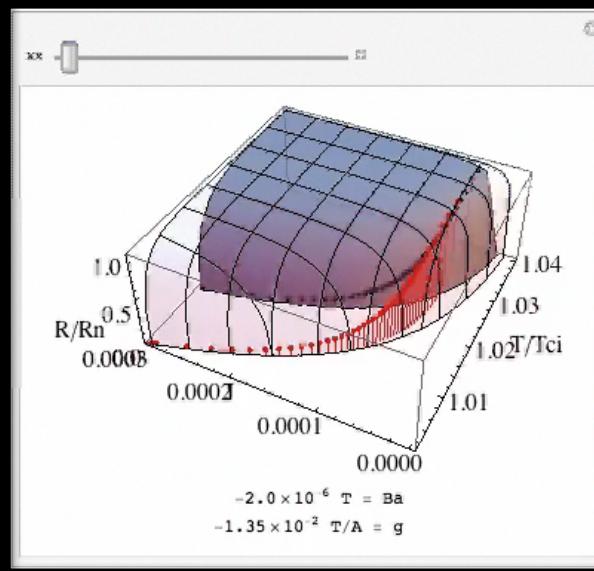
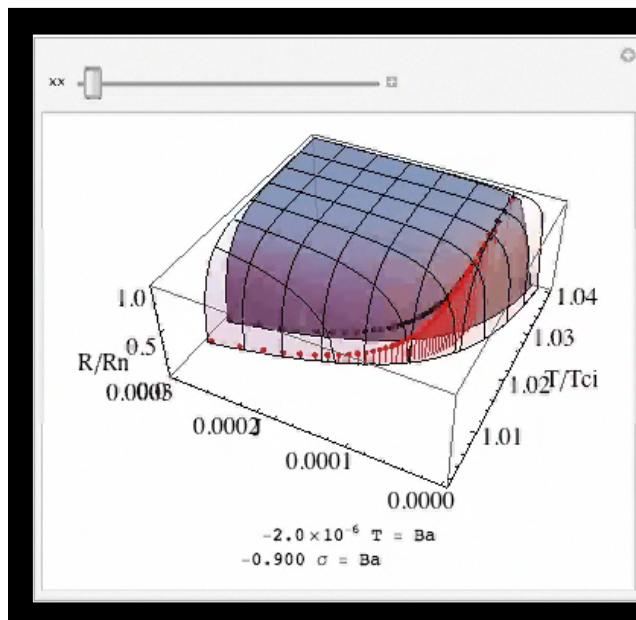


Small self-fielding g
 $\beta \rightarrow \beta_l$

Moderate self-fielding g
 $\beta \rightarrow 0$ at small R/R_n

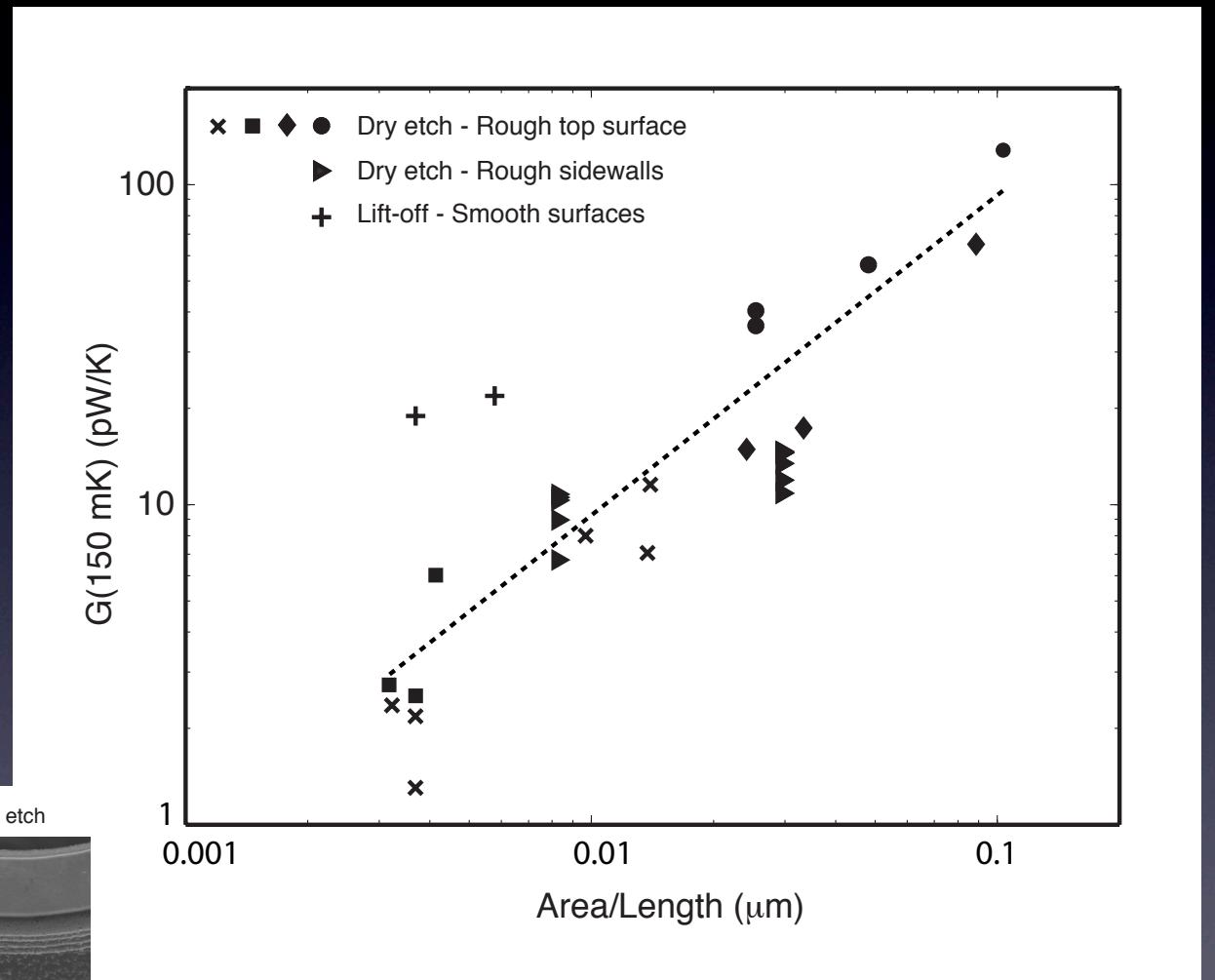
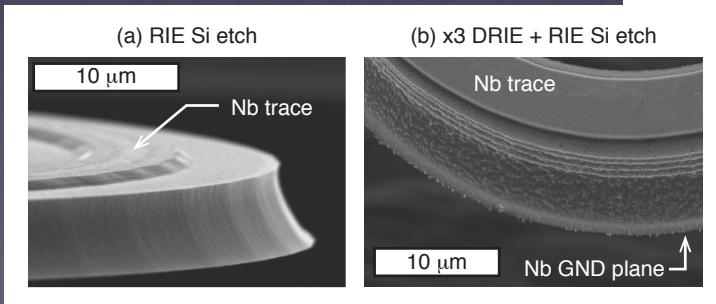


Large self-fielding g
 $\beta \rightarrow \text{Negative}$ at small R/R_n



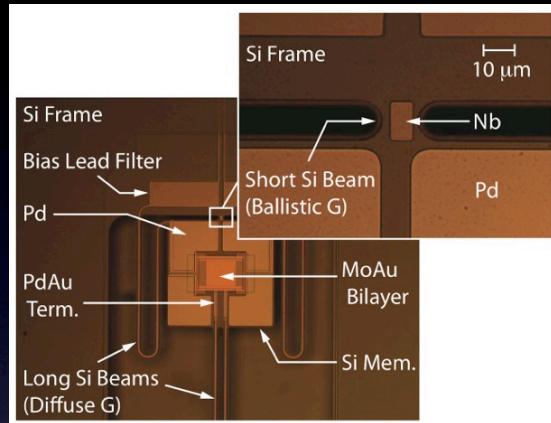
Thermal Conductance

- Review of literature and discussions reveal ~50-80% variability commonly observed in diffusive Si leg designs.
 - Improvement desired to improve yield given other realities in fabrication.

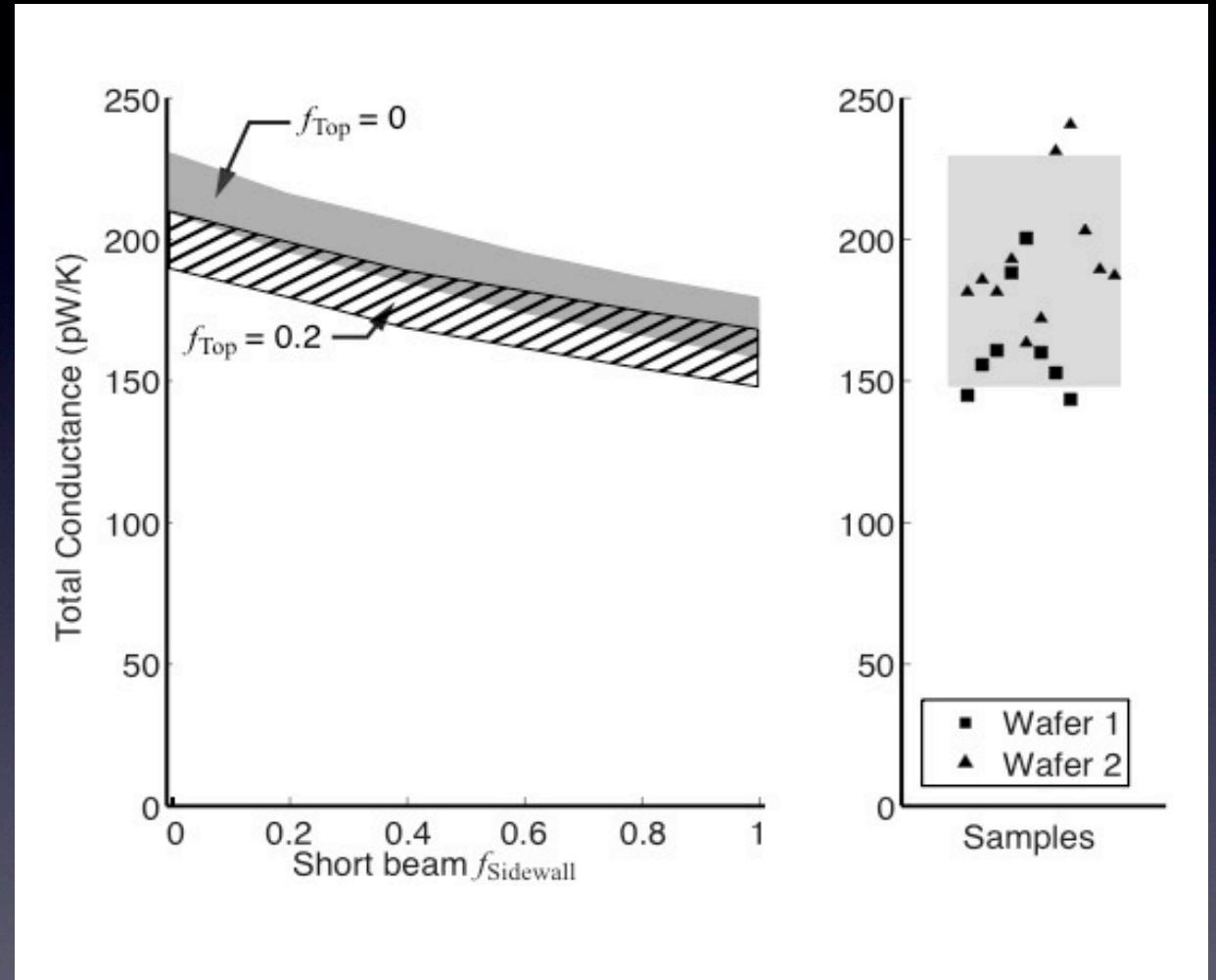


Rostem et al. (2014)

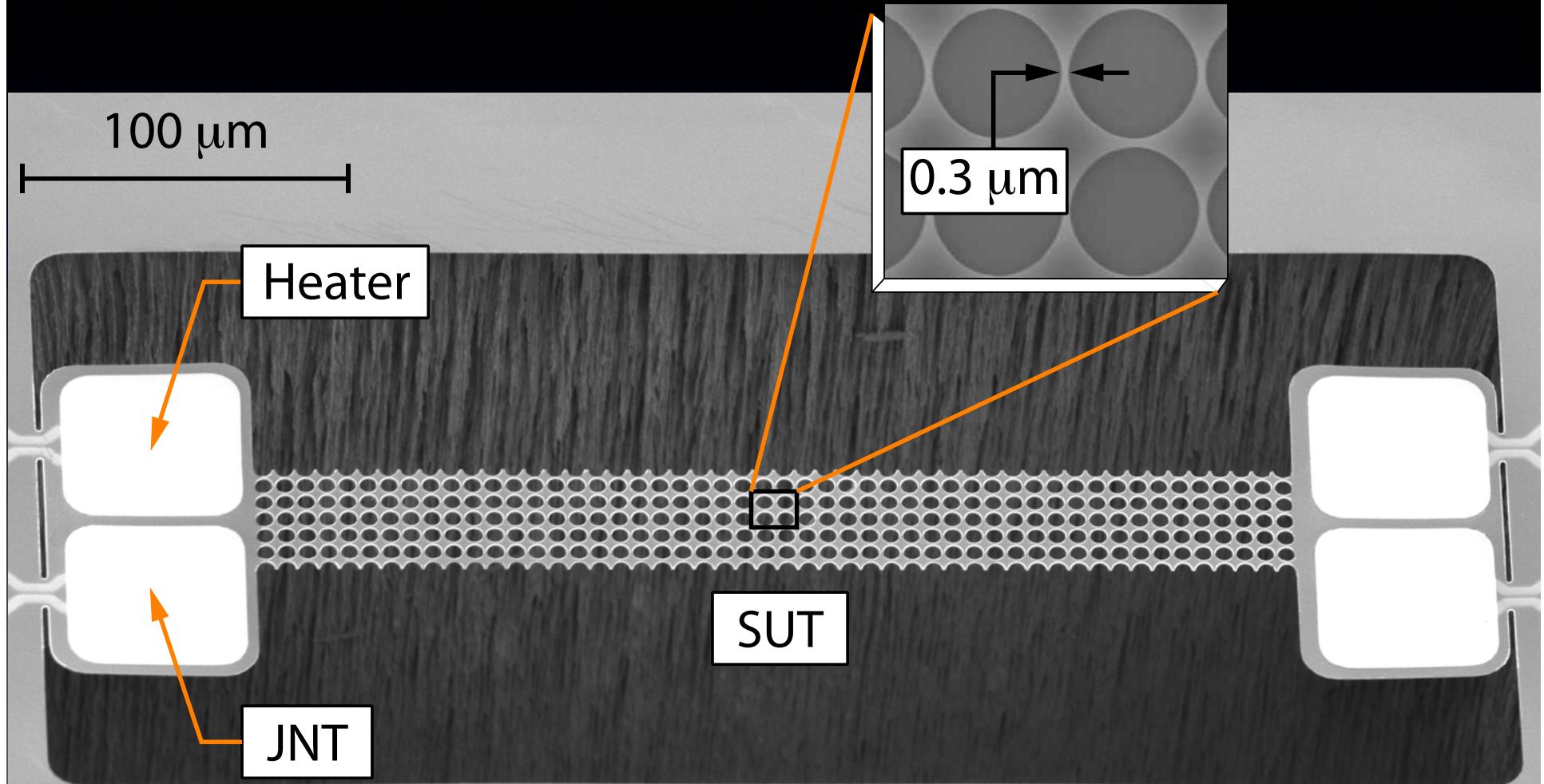
Thermal Conductance



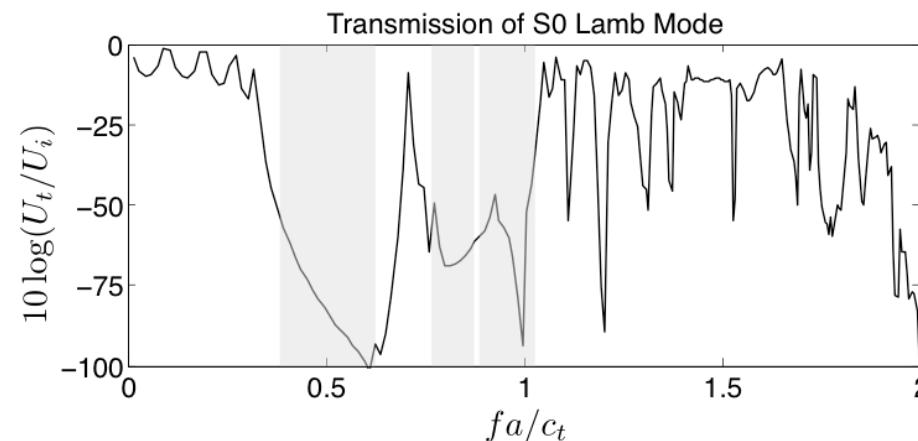
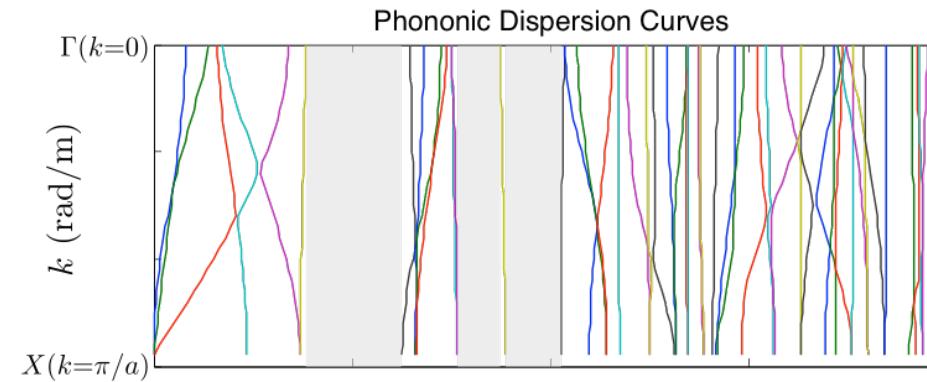
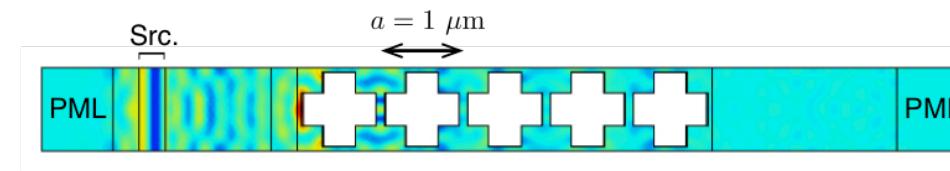
- New leg designs have achieved the target G and exhibit 15% variation
- Improvement over ~50-80% variation observed in typical diffusive leg experience



Phononic Filtering

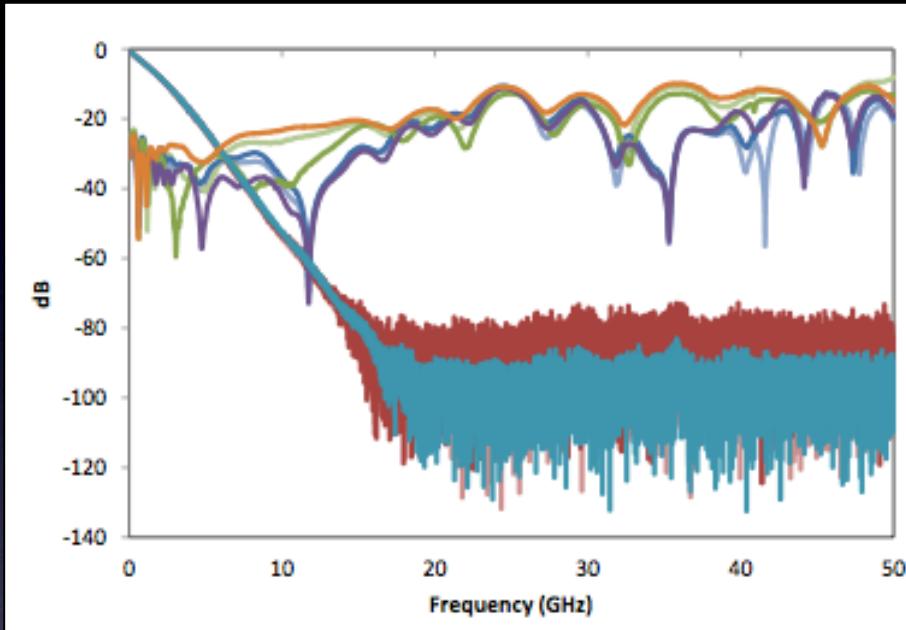


Phononic Stop Bands for Compact Conductance Control



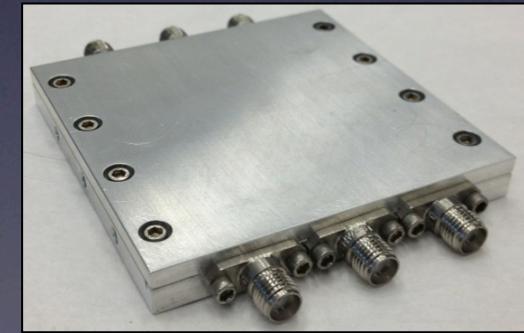
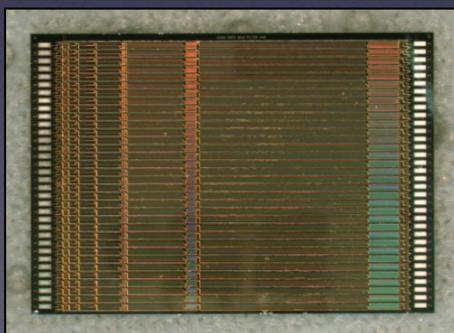
Karwan Rostem

Thermal Blocking Filters



Simple “Matched” Filter...
Steel Loaded Epoxy
 $\epsilon_r \sim 10.3 + 1.8i$
SMA connector interface

...easy to make and Repeatable.



U-Yen and Wollack (2008)
Wollack, et al., (2014)

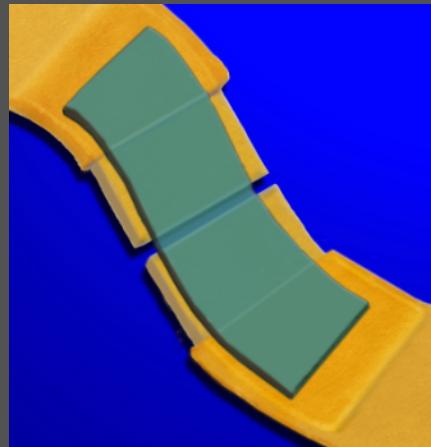
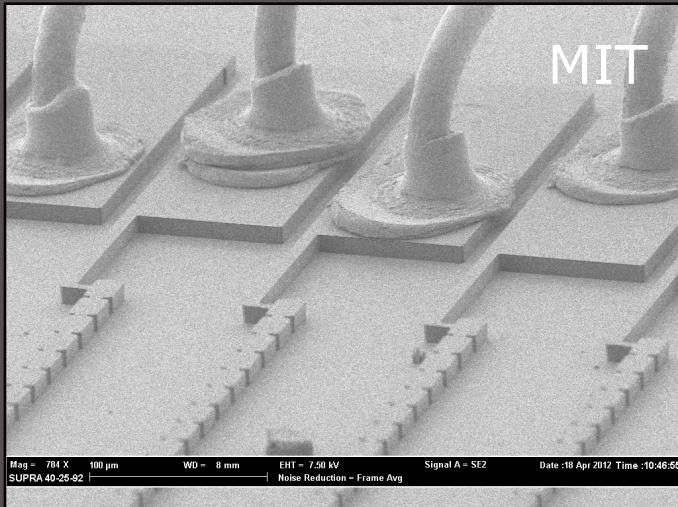
Demonstrated 4.7 THz heterodyne technology

LO

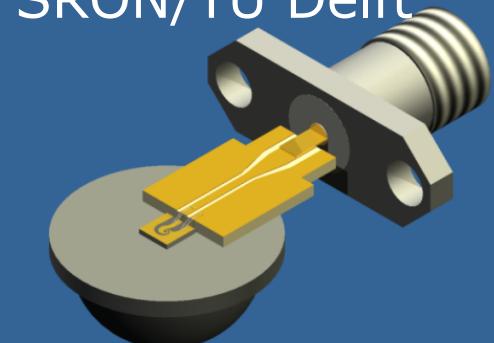
- Advanced 3rd order distributed feedback QCL
- Output: 0.25 mW
- DC input: 0.7 W
- Frequency locked

Mixer:

- Superconducting NbN HEB mixer
- Spiral or twin slot antenna
- $T_{DSB}=810 \text{ K}$ @ 4.7 THz with typically 150 nW LO power

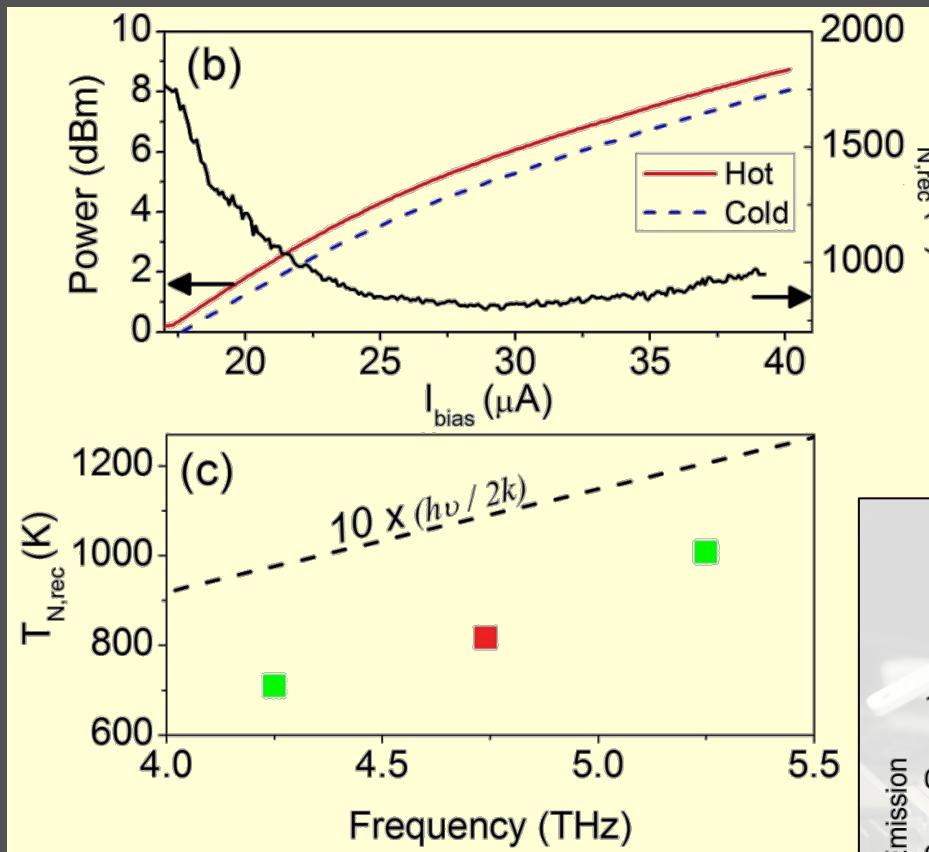


SRON/TU Delft



T.-Y. Kao et al, Optics Letters, (2012)
SRON

Measured Receiver T_N & Gas Spectroscopy at 4.7 THz



$$T_N = 810 \text{ K} @ 4.7 \text{ THz}$$

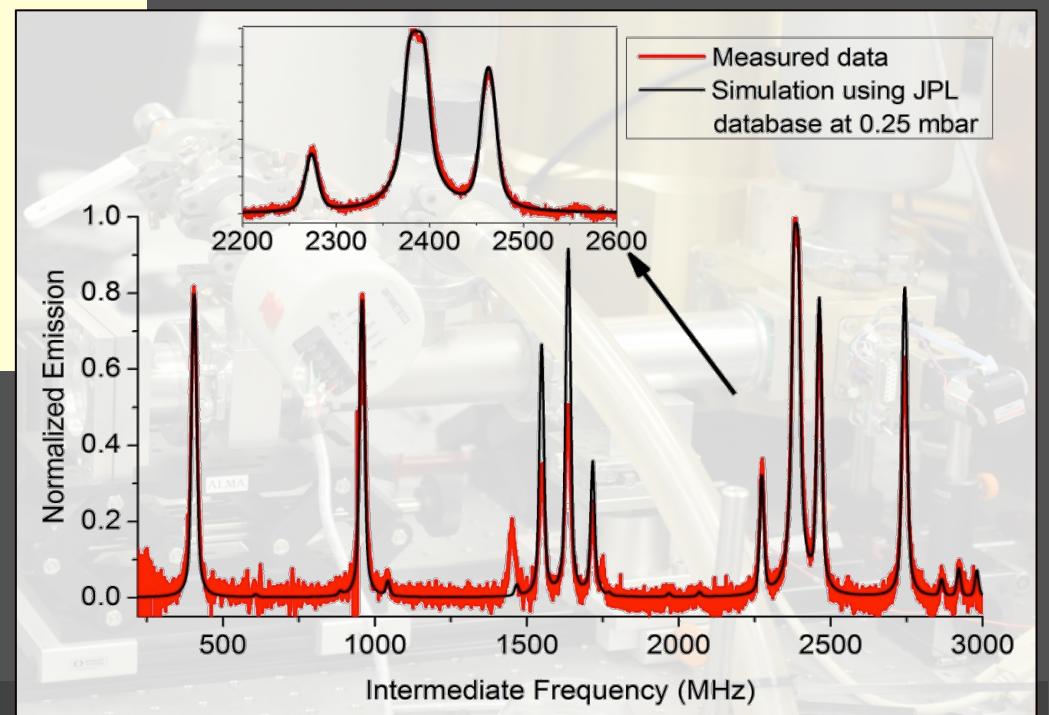
$$\sim 3.5 \times h\nu/k$$

J. L. Kloosterman, D. J. Hayton, Y. Ren, T. Y. Kao, J. N. Hovenier, J. R. Gao, T. M. Klapwijk, Q. Hu, C. K. Walker, and J. L. Reno, APL (2013)

QCL: 4741.0 GHz

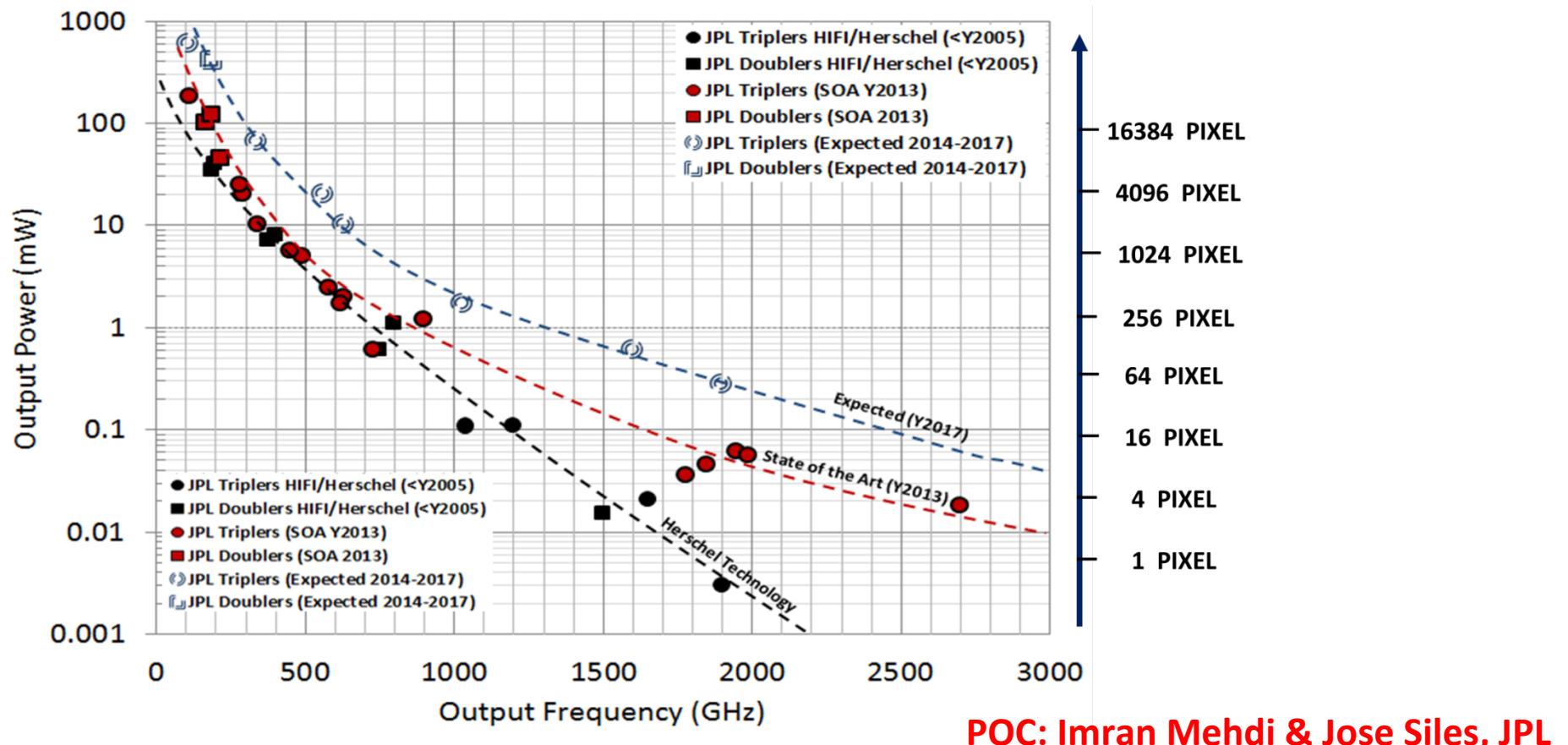
OI: 4744.8 GHz

\rightarrow 3.8 GHz IF USB



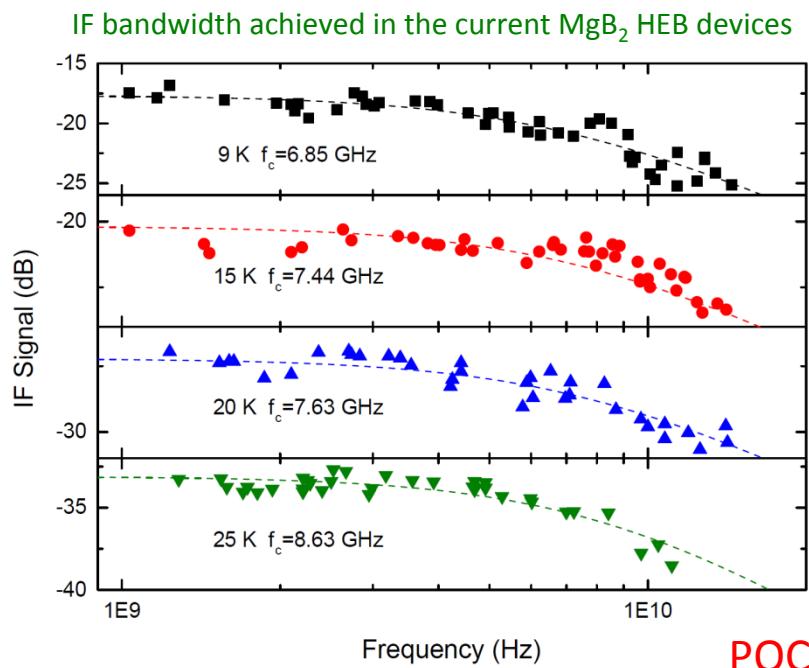
Electronically tunable THz Sources

- Diode technology for room-temperature frequency multiplied sources beyond 1 THz
- *JPL has demonstrated world record performance at 1.9 THz (60 μW) and 2.7 THz (14 μW)*
- Better optimized designs together with novel topologies will make possible an increase of one order of magnitude in output power
- We expect to extend the operating frequency up to 4.7 THz within 3 years (APRA funded)

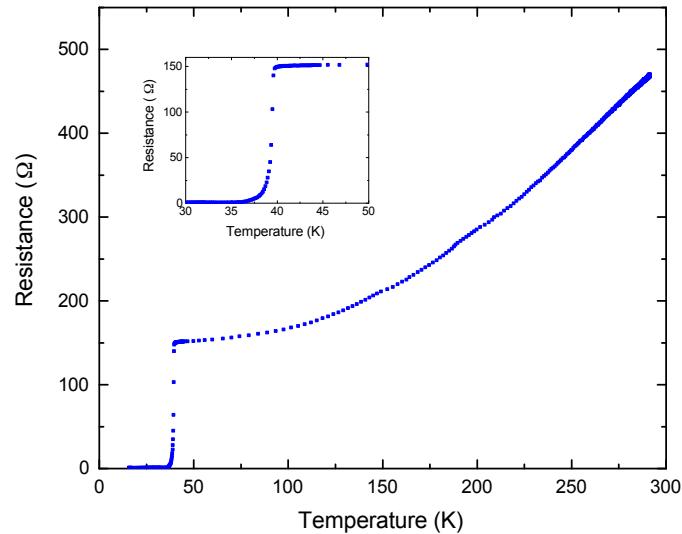


Next Generation of HEBs: Ultrabroadband MgB₂ based THz mixer operating above 20 K (D. Cunnane, J. Kawamura, and B. Karasik – JPL, M. Wolak and X. Xi – Temple Uni.)

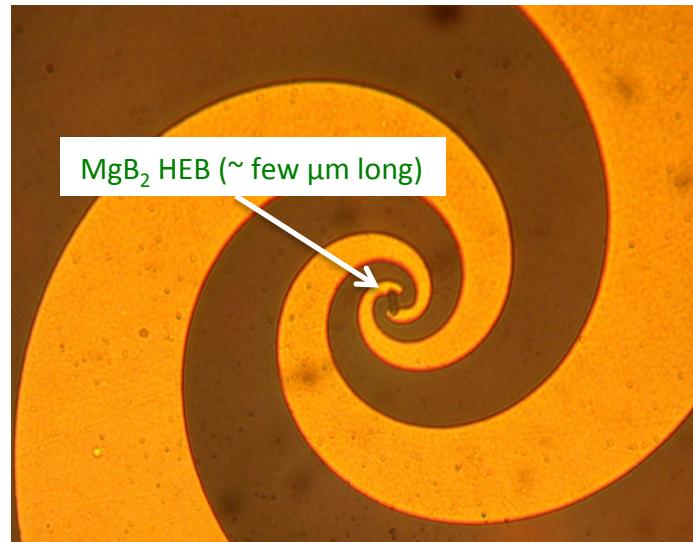
- The novel THz mixer based on thin-film superconducting MgB₂ will have an IF bandwidth 10+ GHz (currently, 8.6 GHz) and operate above 20 K requiring only a few μ W of local oscillator power.
- The main impact will be on space instruments where cryocooling to 4 K required by the SOA HEB NbN mixers is challenging.
- A 3-fold increase of the IF bandwidth compared to the SOA mixers will allow for observation of Doppler broadened extragalactic THz lines (e.g., [OI] at 4.7 THz).



Superconducting transition in a 25-nm thin MgB₂ device



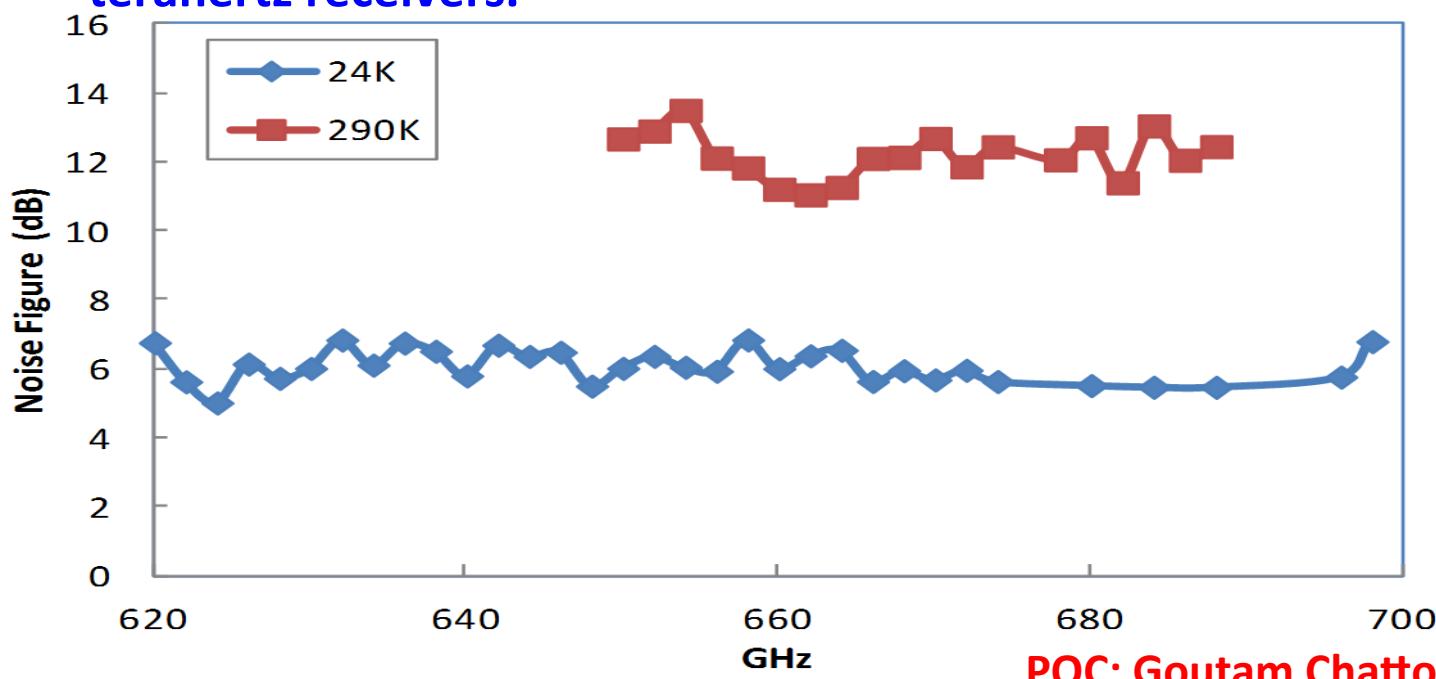
Antenna-coupled quasioptical mixer device



POC: Boris Karasik, JPL

InP HEMT Low-Noise Amp Technology

- Cryogenic amplifiers at 640 GHz are showing almost a factor of eight improvements in noise temperature when cooled to 20K, similar to amplifiers at millimeter wavelengths.
- It is now feasible to design and develop HEMT based receivers which will offer performance close to SIS mixers, but at 20K.
- Integrating mixers and frequency multipliers on the same chip leads to highly integrated receivers – opens the door for multi-pixel cooled terahertz receivers.



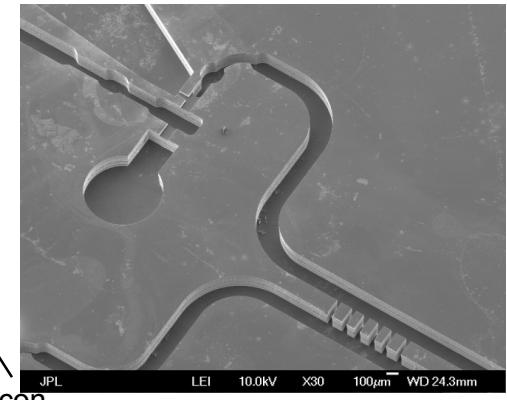
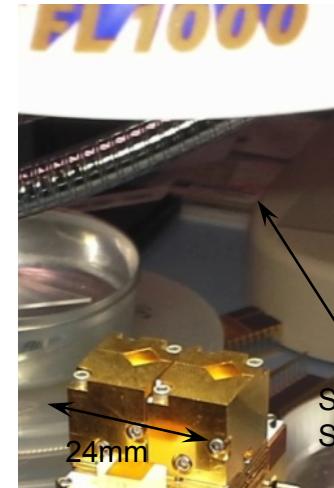
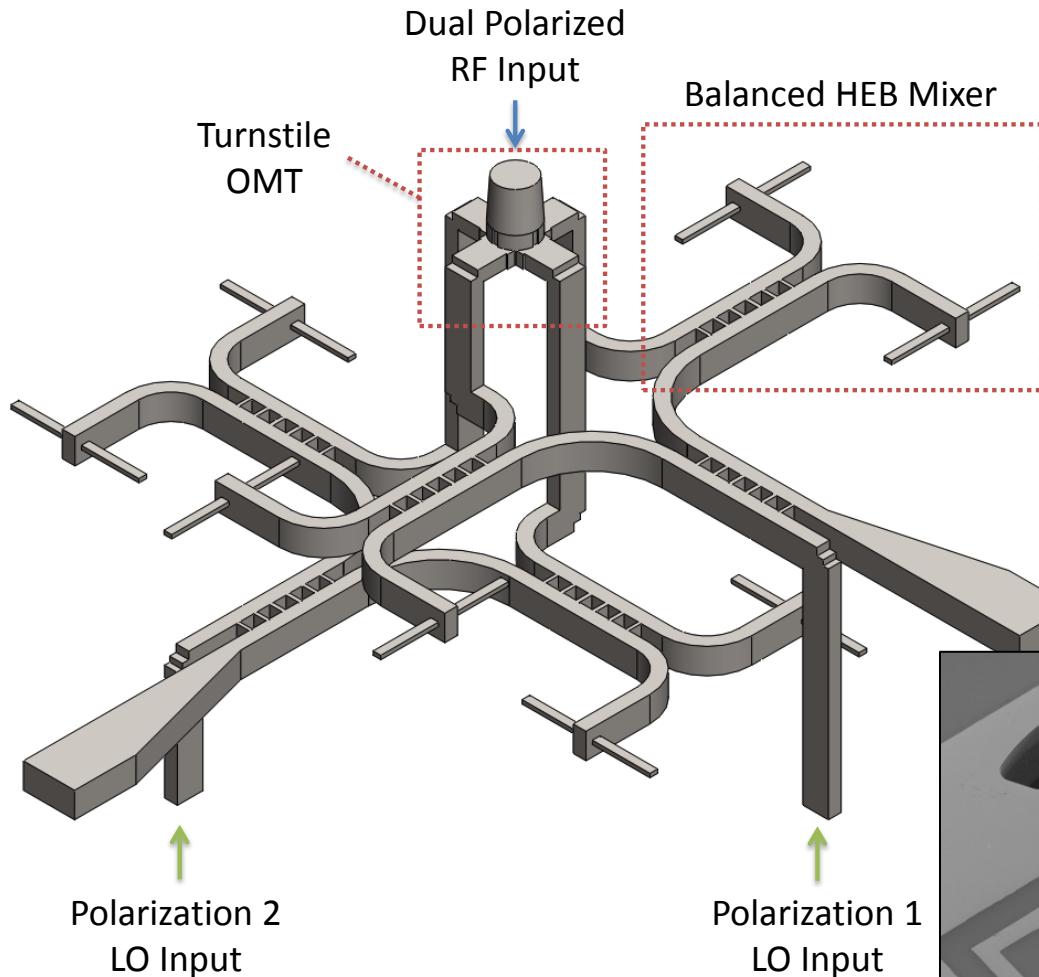
POC: Goutam Chattopadhyay, JPL

Summary

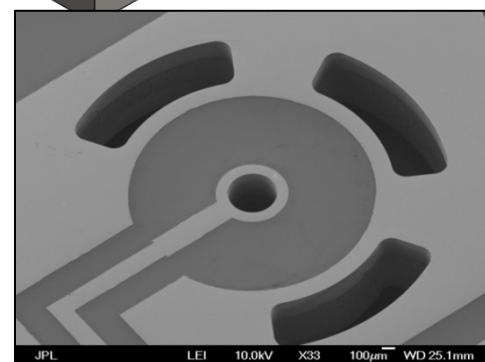
- There is a large concentration of talent making rapid progress in FIR/SMM detectors and developing new technologies
- Clear development paths exist for arrays of tens of thousands of detectors
- Current detectors can provide background limited performance in a broad band cryogenic space environment
 - Paths to higher sensitivity are clear
 - Power detection and photon counting
 - Photon counting has fundamental benefits
 - We must set scientific goals to drive development in the right directions

Silicon Micromachined Heterodyne Array at 1.9 THz

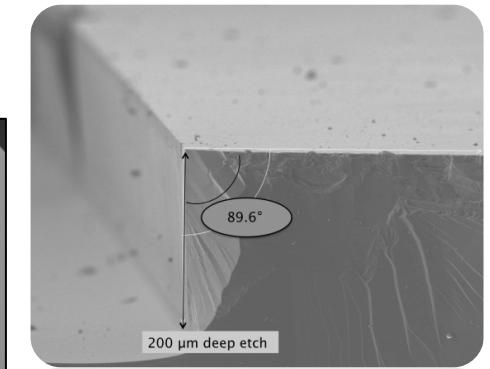
This technology allows for super-compact components



Micromachined waveguide parts

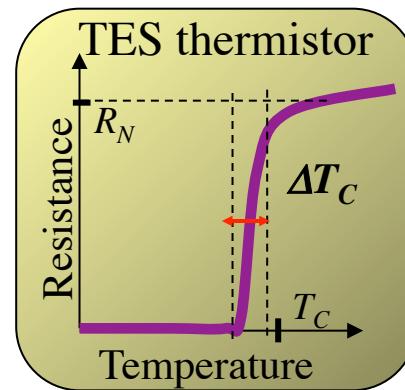


Micromachined Co-axial IF Output



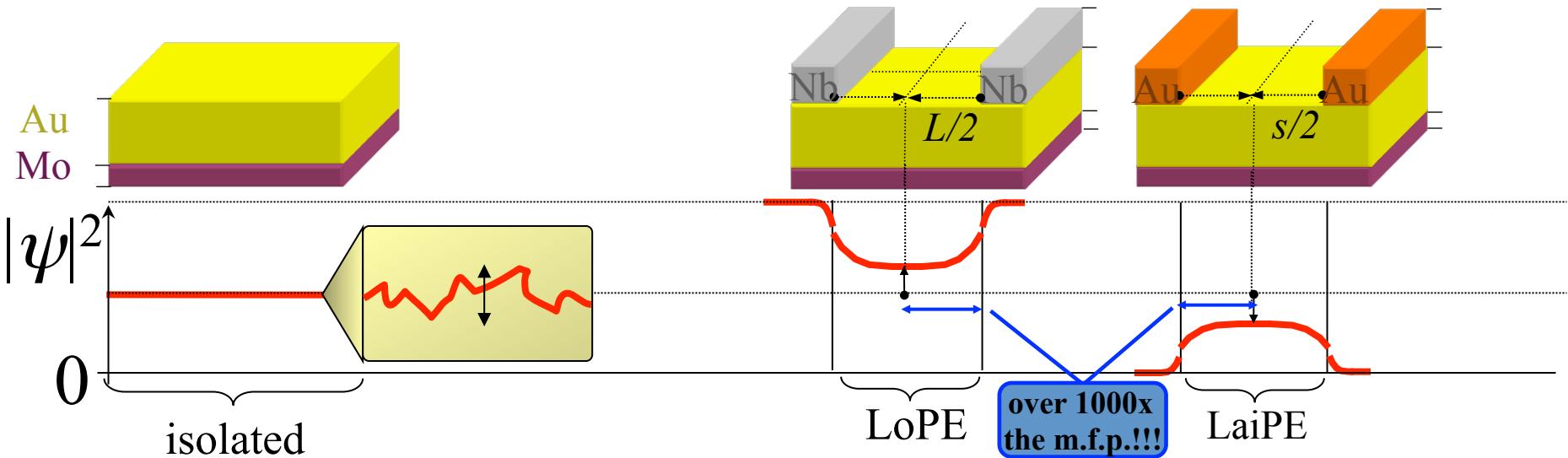
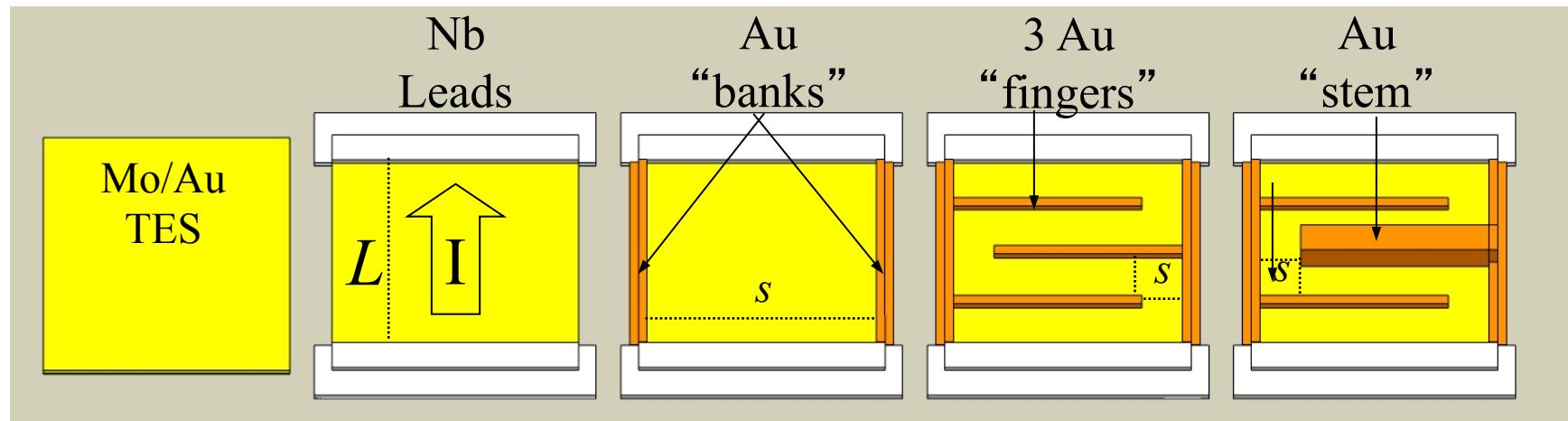
Excellent Straight Sidewalls for Deep Etching

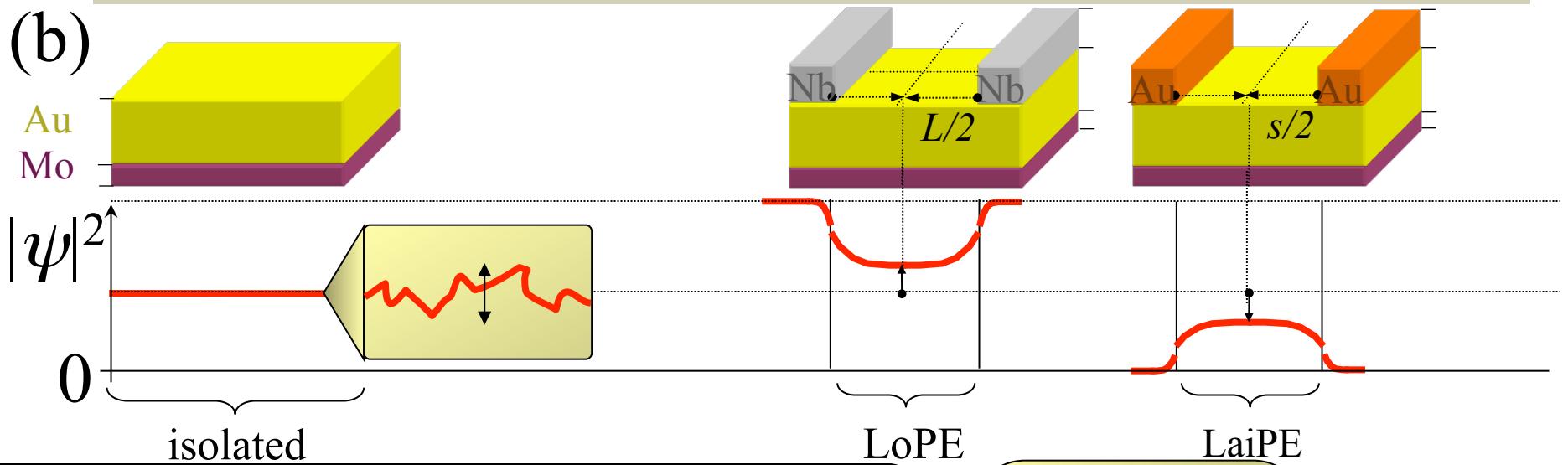
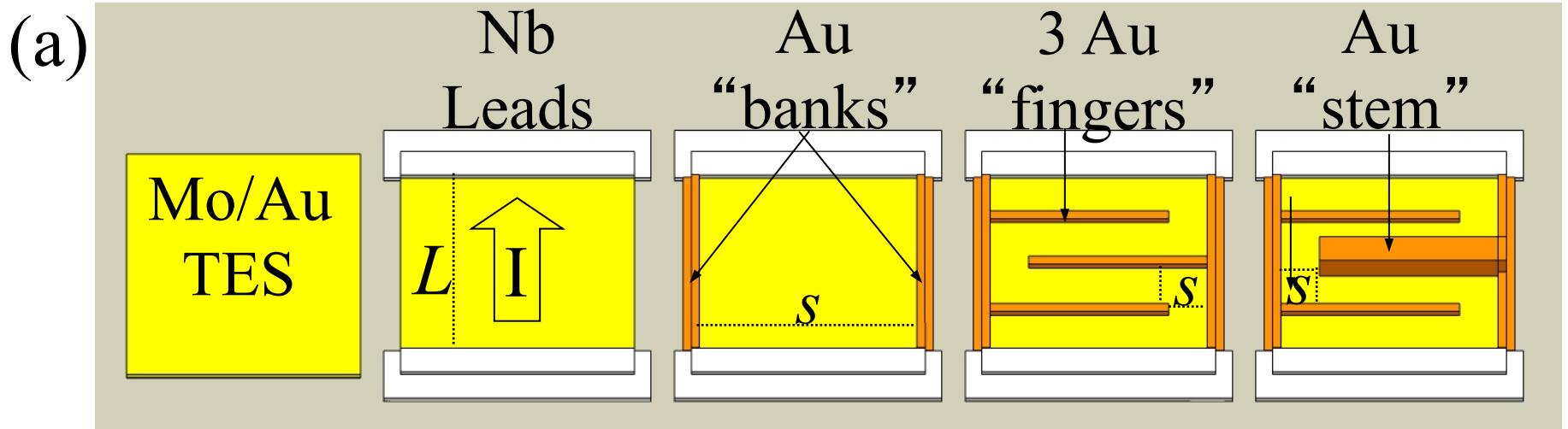
POC: Goutam Chattopadhyay, JPL



Assumes TES is a
Uniform Superconductor
(any $|\psi|^2$ variation is random)
S.C. Theory

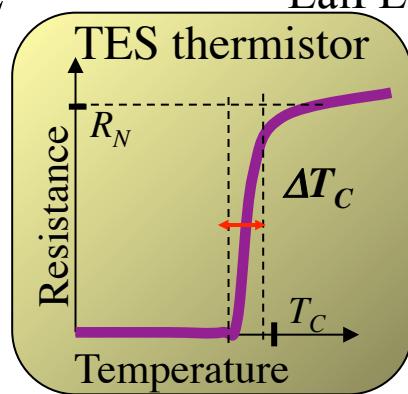
KT theory $\rightarrow \Delta T_c \approx 1 \text{ nK}$
AL & MT theory $\rightarrow \Delta T_c \approx 1 \mu\text{K}$
BUT Measured $\Delta T_c \sim 0.5 \text{ mK}$

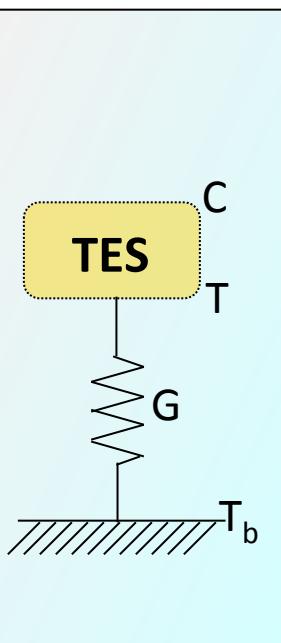
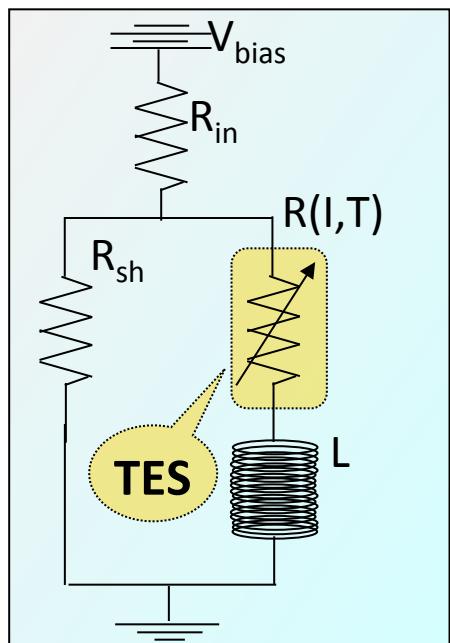




Assumes TES is a
Uniform Superconductor
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S.C. Theory
KT theory $\rightarrow \Delta T_c \approx 1 \text{ nK}$
AL & MT theory $\rightarrow \Delta T_c \approx 1 \mu\text{K}$
Measured $\Delta T_c \sim 0.5 \text{ mK}$





$$C \frac{dT}{dt} = I^2 R(T,I) + P_{\text{sig}} - P_b$$

$$L \frac{dI}{dt} = V - IR_{\text{sh}} - IR(T,I)$$

Linearize Coupled Diff Eqs
+Johnson Noise
+Phonon Noise
+Extra noise M^2 e.g. SC

$$\alpha \equiv \left. \frac{T}{R} \frac{dR}{dT} \right|_I \quad \beta \equiv \left. \frac{I}{R} \frac{dR}{dI} \right|_T$$

Strong ETF limit

$$\Delta E_{\text{FWHM}} \approx 2.35 \sqrt{4k_b T^2 \frac{C}{\alpha} \sqrt{\frac{3}{2}(1+2\beta+\theta)(1+M^2)}}$$

$R(I,T)$

&

$\beta, \alpha,$
 $T_c, \Delta T_c,$
 $I_c,$
 $K_x(y, T)$
 $B, \text{etc.}$

Intrinsic Noise, M^2

- e.g. Superconductivity
- $M^2 = ? \geq 0$
- $M^2(\beta, \alpha, ?)$

- ? *R-network percolation*
- ? *internal thermal fluctuation noise*
- ? *vortex noise*
- ? *fluctuation superconductivity*
- ? *phase slip line formation*
- ? *vortex channel number*
- ? *nonequilibrium superconductivity*
- ? *Kosterlitz-Thouless (KT) vortex-antivortex pair fluctuations*
- ? *other*

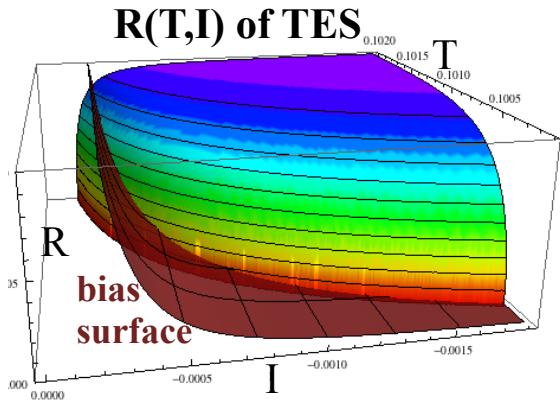
&

Nonlinear & Nonequilibrium Effects

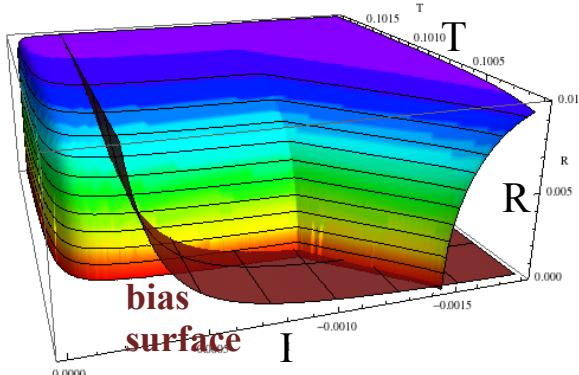
- e.g. nonlinear Johnson Noise
- $4k_B T R(1+2\beta+\theta)$
- $\theta = ? \geq 0$
- $\theta(\beta, \alpha, ?)$

Reduced β AND increased α for MTES = “magnetically tuned TES”

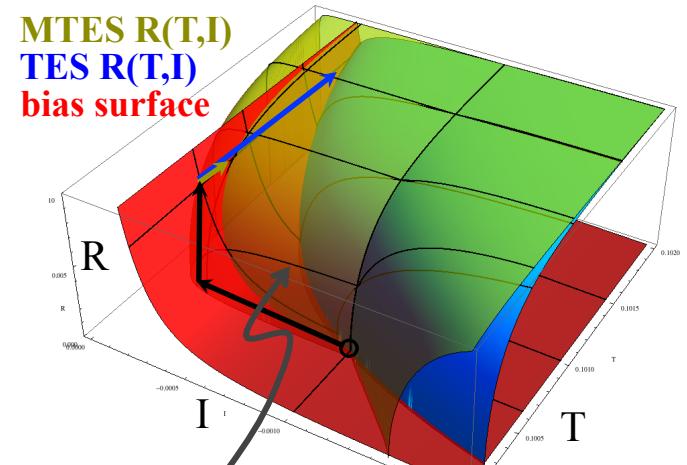
$$R(\underline{T}) \Rightarrow R(T, \underline{I}) \Rightarrow R(T, I, \underline{B})$$



R(T,I) of MTES



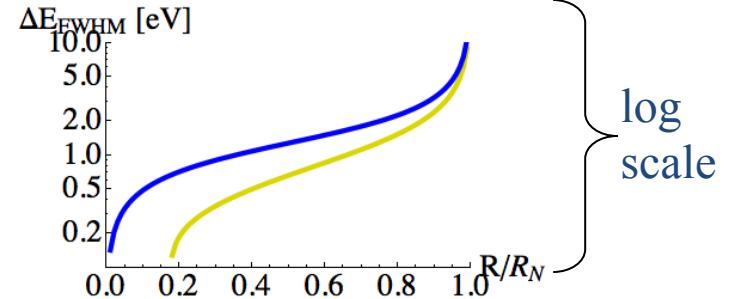
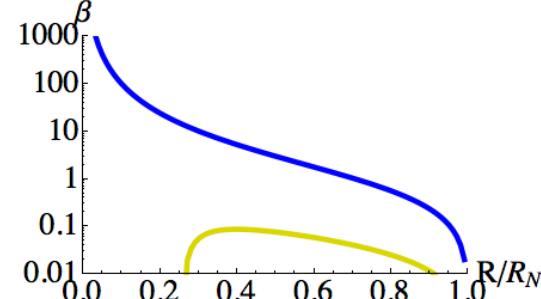
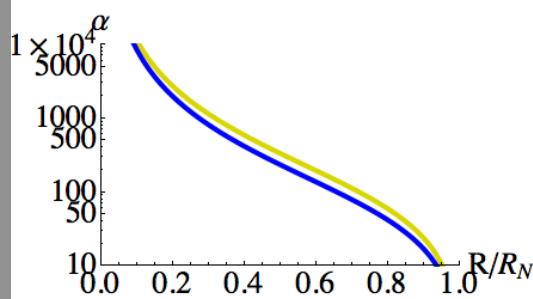
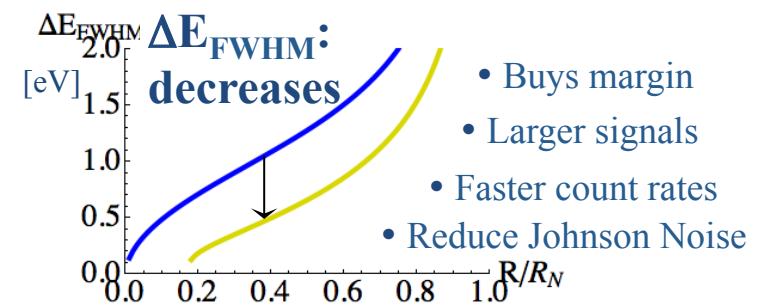
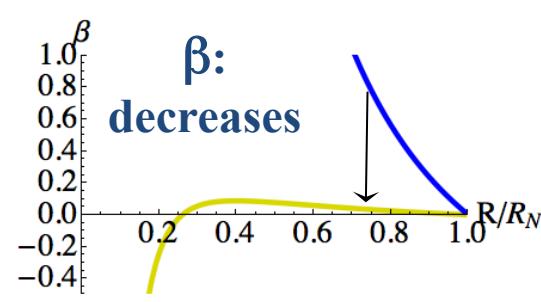
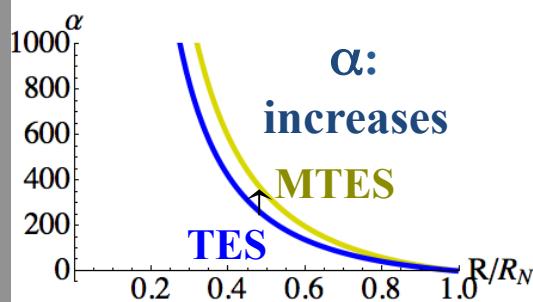
- β : decreases
- α : increases
- τ_{ETF} : decreases, (Faster count rates)
- PH: increases, (Larger signals)
- Noise: decreases (Reduced Johnson Noise)
- ΔE_{FWHM} : decreases (Improved Energy Resolution)



Yellow MFB R(T,I) surface has:

- (1) made the $R(I)|_T$ contours $\partial R / \partial I \approx 0$
therefore $\beta \approx 0$.
- (2) maintained a large α
(a large $\partial R / \partial T$)
- (3) created the desired large α / β condition over the entire pulse trajectory

MTES = “magnetically tuned TES”...
can enjoy reduced β AND increased α over the entire pulse trajectory!



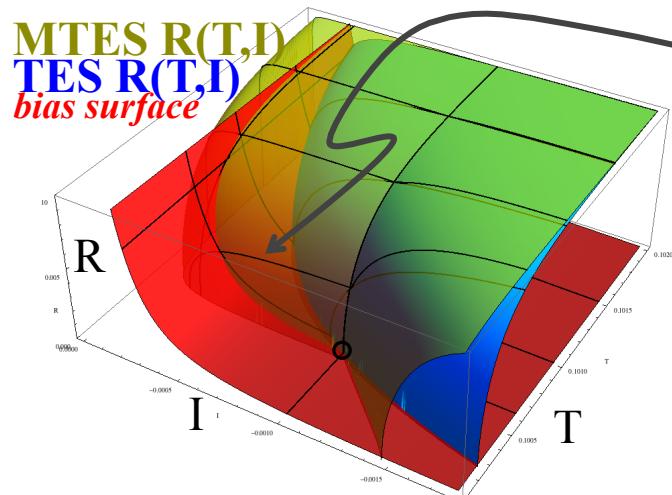
MTES = “magnetically tuned TES”... reduced β AND increased α

J.E. Sadleir et al. (Wednesday 11:15am)

$$R(T, I, B) \approx R_0 + \alpha \frac{R_0}{T_0} \delta T + \beta \frac{R_0}{I_0} \delta I$$

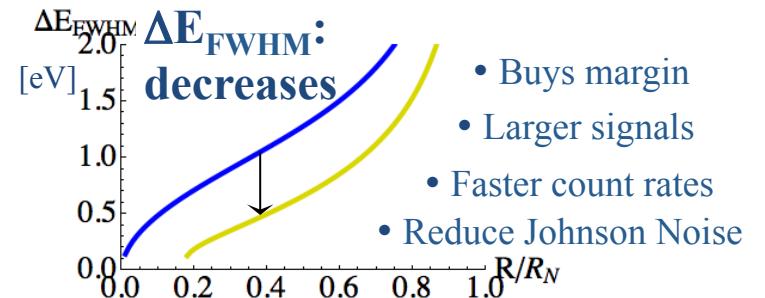
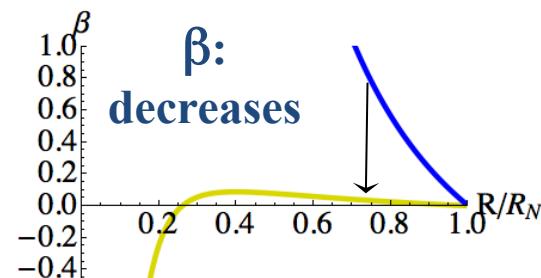
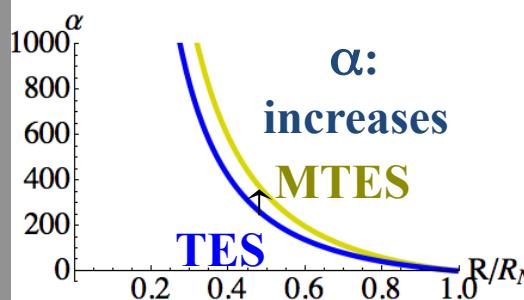
$$\beta \equiv \beta_{meas} = \beta_I + \beta_B$$

$$\beta = \beta_I + \frac{g I_0}{R_0} \frac{\partial R}{\partial B}$$

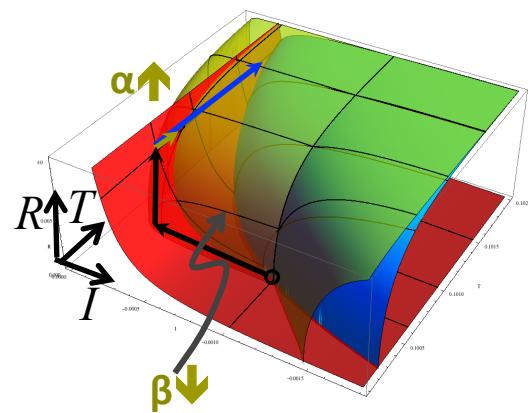


*Magnetically tuning the
TES R(T,I) surface \Rightarrow MTES R(T,I) surface
(Blue) \Rightarrow (Yellow)*

- (1) made the $R(I)|_T$ contours $\partial R / \partial I \approx 0 \Rightarrow \beta \approx 0$.
- (2) maintained a large α (a large $\partial R / \partial T$)



Bias circuit constraint surface
TES's Original $R(T,I)$ surface
Predicted MTES $R(T,I)$ surface



Goal: $\beta \downarrow, \alpha \uparrow$

$$\beta \sim \frac{\partial R}{\partial I} \quad \alpha \sim \frac{\partial R}{\partial T}$$

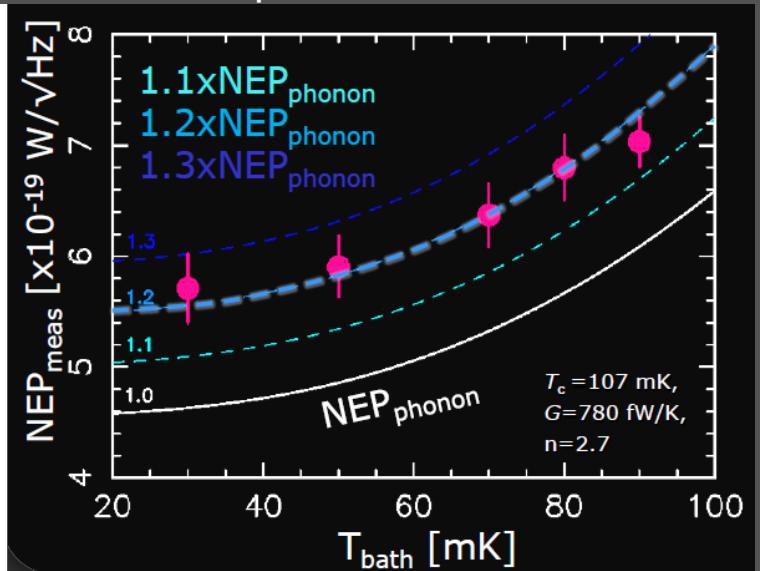
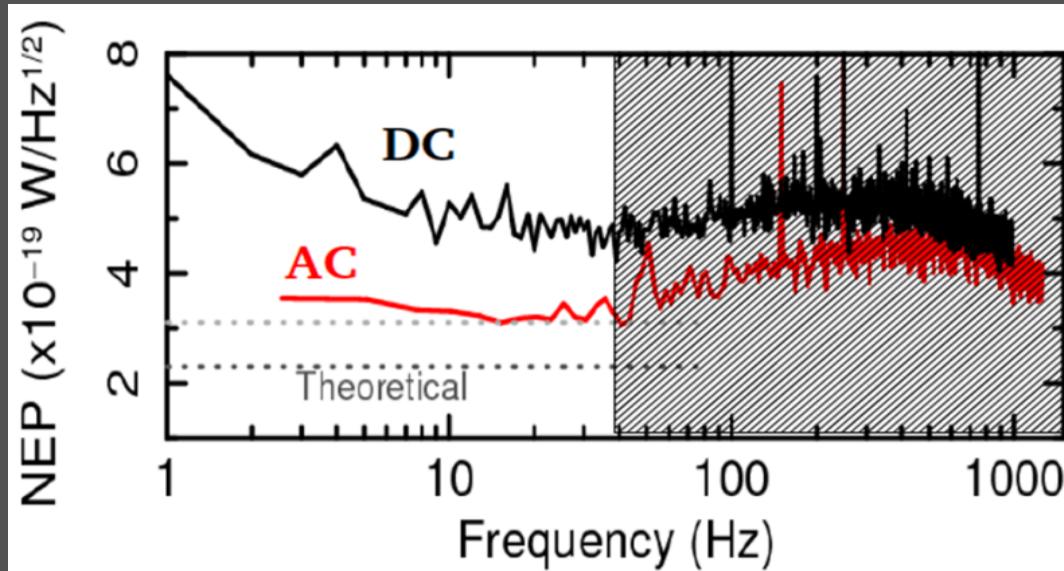
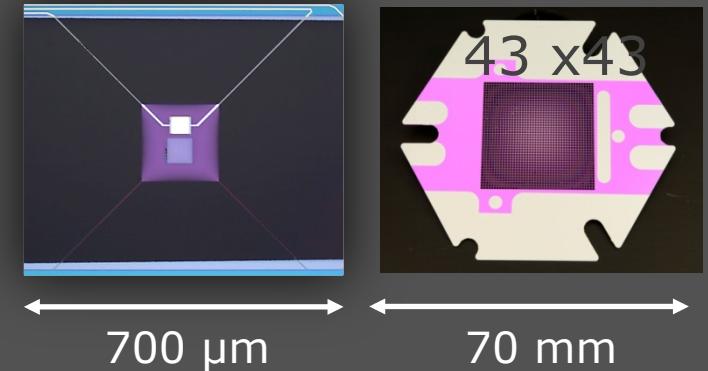
$\alpha \uparrow$: MTES larger R change
 for same change in
 temperature T.

$\beta \downarrow$: MTES smaller change in
 R for the same change in
 current I.

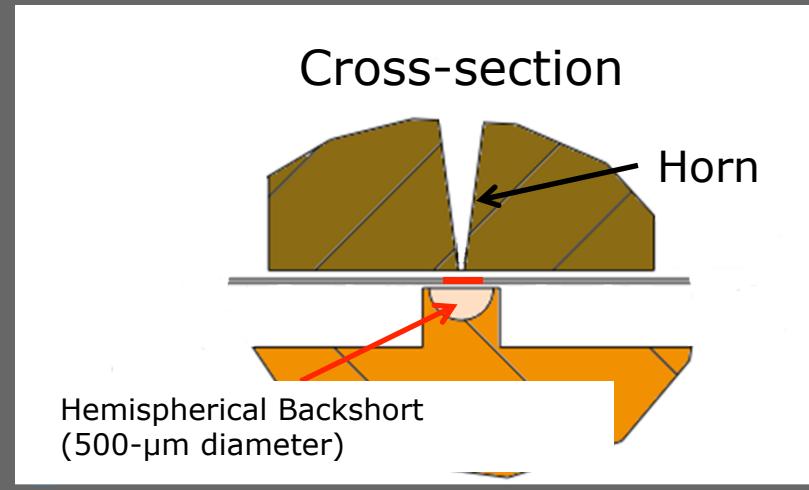
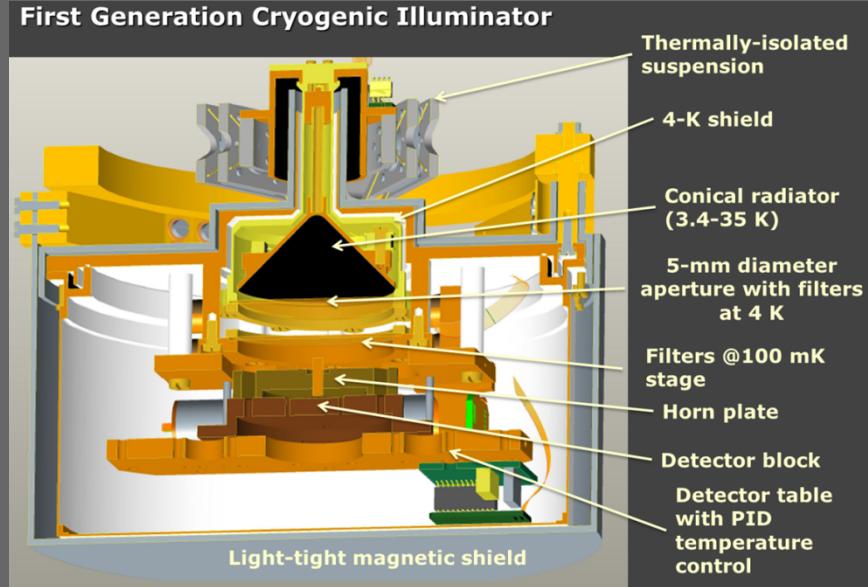
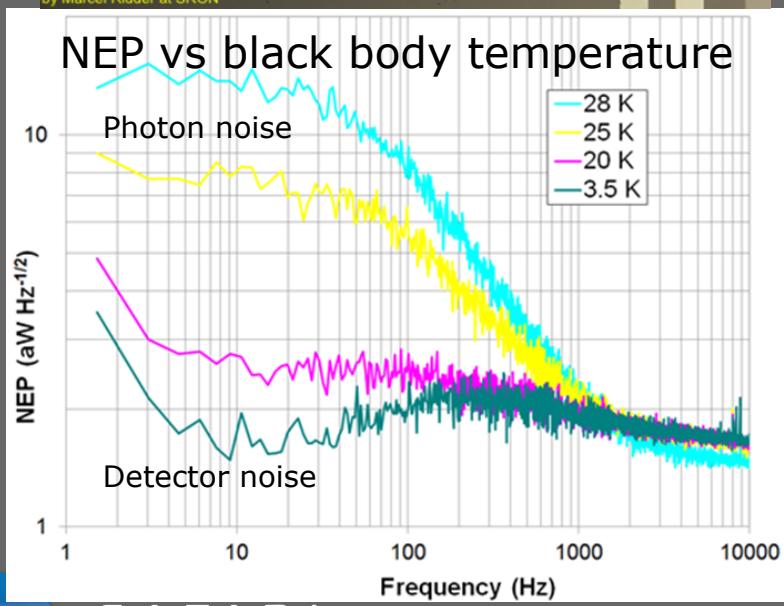
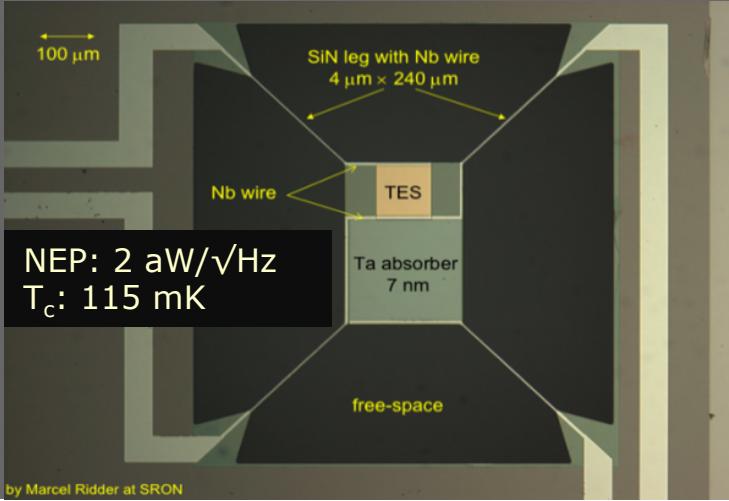
TES array for SAFARI/SPICA

TES arrays for Short wavelength band

- Electrical NEP under AC: $3 \times 10^{-19} \text{ W}/\sqrt{\text{Hz}}$ (opt efficiency: 40%).
- NEP seems to follow the model
- With Deep-RIE we are progressing SAFARI large array (43x43)



SRON: Single-Pixel horn-coupled TES photon noise limited optical measurements @ 30-60 μm with $\text{NEP} \sim 10^{17}-18 \text{ W}/\sqrt{\text{Hz}}$

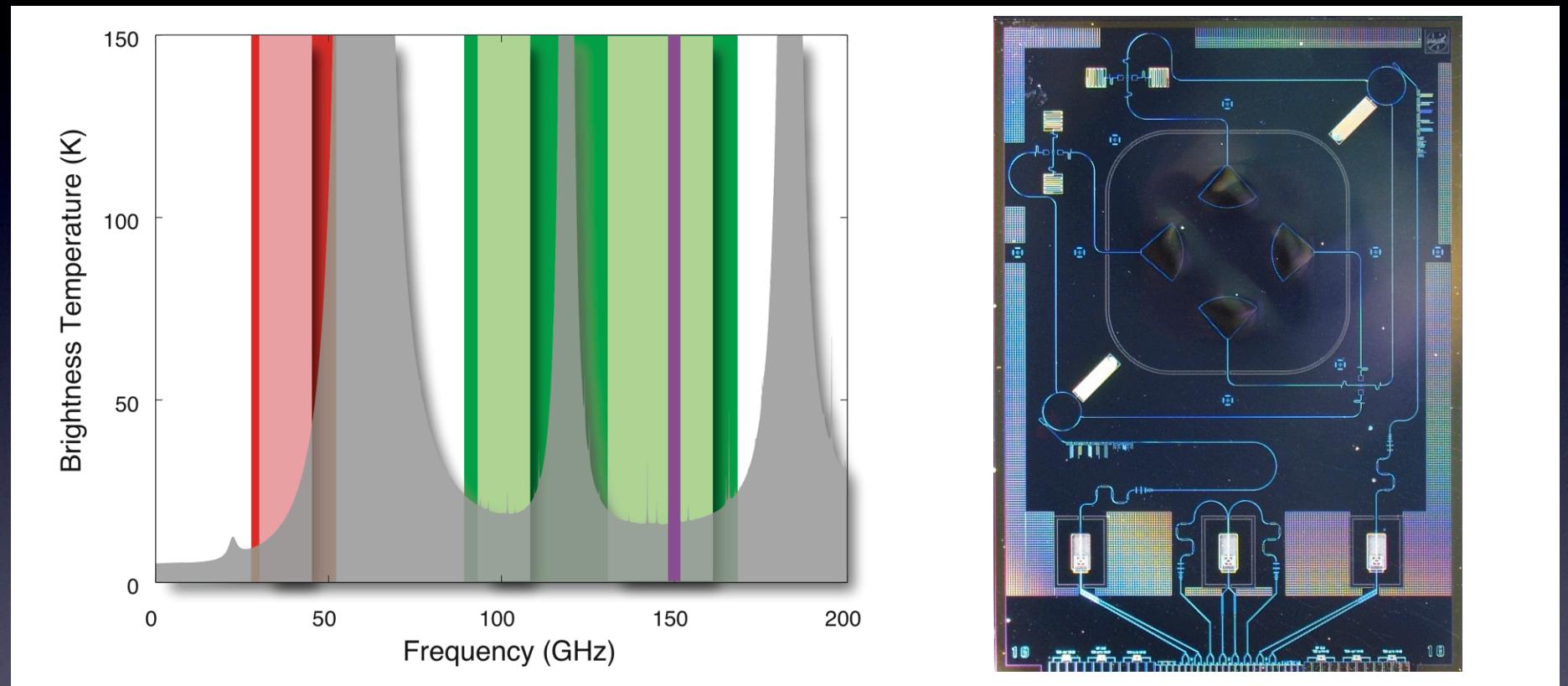


SAFARI
SRON

SRON Netherlands Institute for Space Research, M.D. Audley, G. de Lange

60

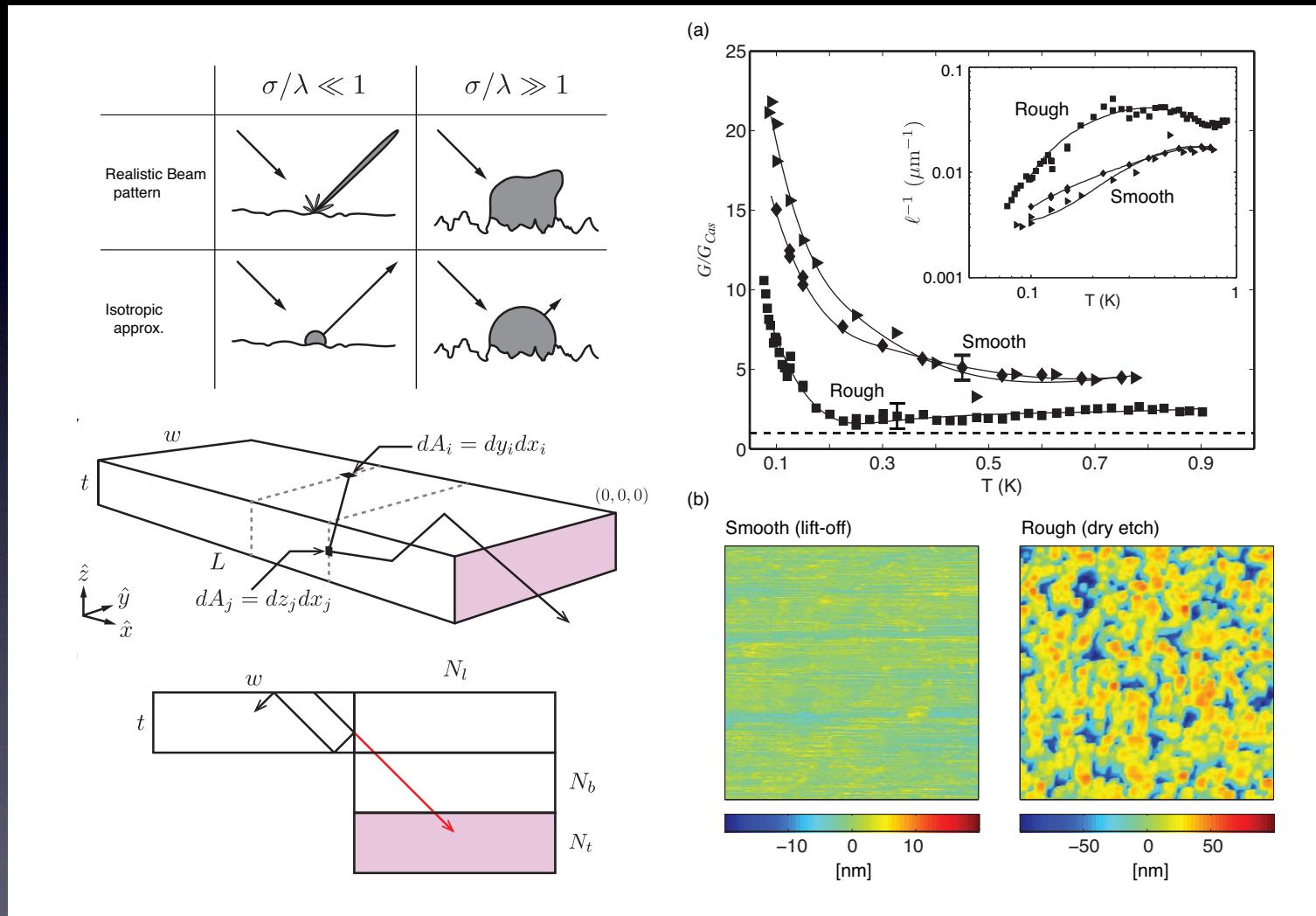
40 GHz Frequency Response



- Symmetric OMT has wide intrinsic bandwidth
- Filtering scheme inherently flexible

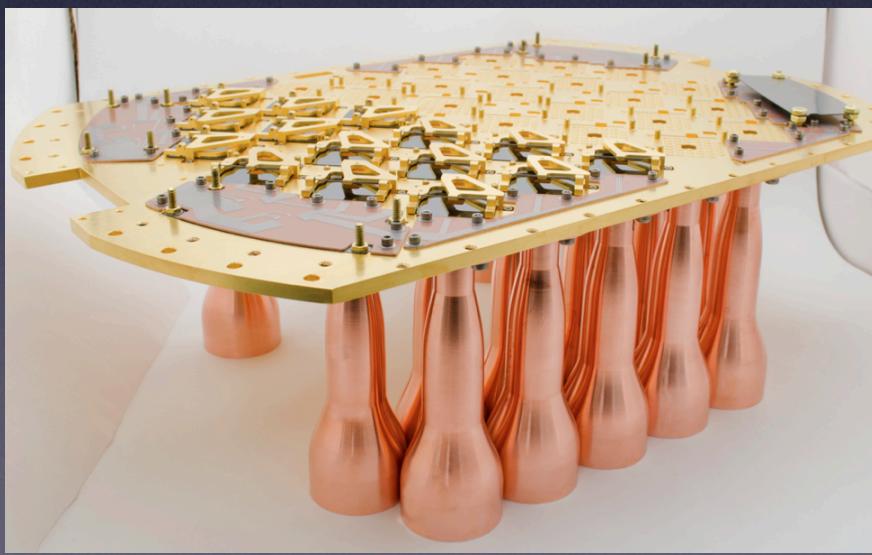
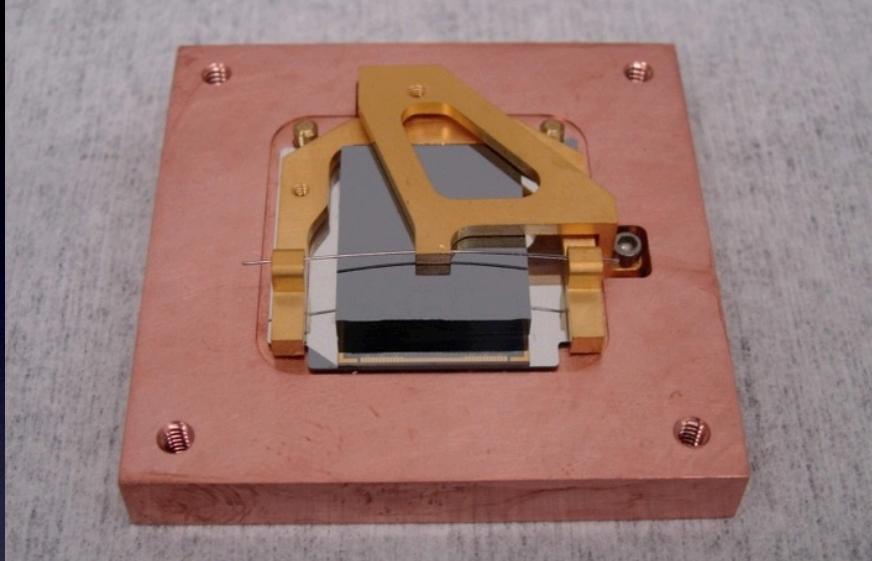
U-Yen et al. (2007, 2008, 2009)
U-Yen & Wollack (2008)

Thermal Conductance

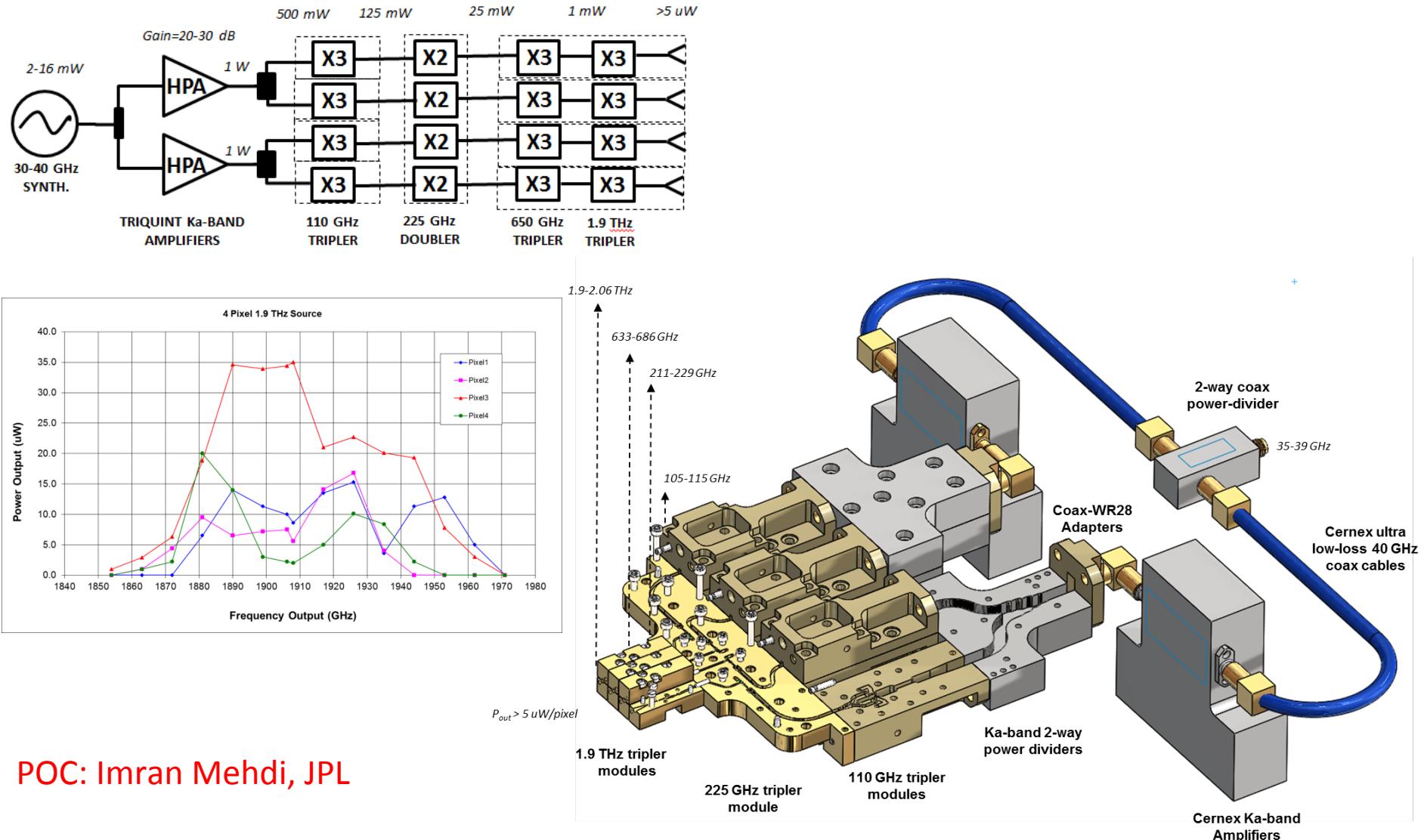


Rostem et al. (2014)

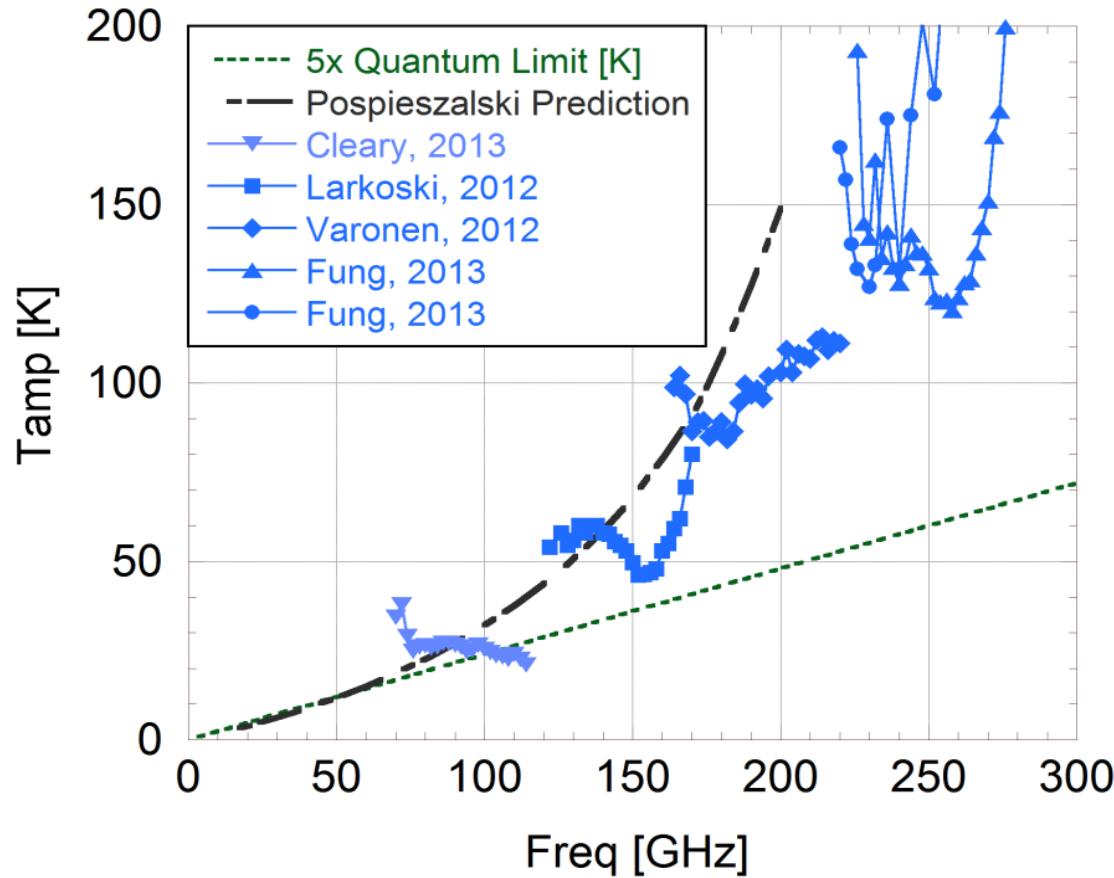
CLASS 40 GHz Focal Plane



First Ever 4-pixel LO for 1.9 THz



Near Quantum Limited Cryogenic Noise in InP Low Noise Amplifier MMICs



Data contributions from L. Samoska, M. Varonen, P. Larkoski, A. Fung, K. Cleary, P. Kangaslahti, T. Gaier, JPL, Caltech, Stanford, 2014.

- Noise temperature in Kelvin for a range of LNA MMICs designed at JPL and cooled to 20K ambient temperature (readily achievable with inexpensive cryocoolers).
- The Pospieszalski prediction of 1990 has been surpassed at nearly all frequencies tested to date, and MMIC LNAs are rapidly approaching 5 x the quantum limit.

POC: Dr. Lorene Samoska, JPL